2nd FLOOR

The Journal of
THE ROYAL AERONAUTICAL SOCIETY

CONTENTS SEPTEMBER 1948

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DOWTY EQUIPMENT LIMITED · CHELTENHAM

THE ROYAL AERONAUTICAL SOCIETY

4 HAMILTON PLACE, PICCADILLY, LONDON, W.1

SEPTEMBER NOTICES 1948

JOURNAL PREMIUM AWARDS

The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members (or non-members) will contribute papers on their own special subjects.

CONTENTS OF THE SEPTEMBER JOURNAL

The Art of the Aviation Engine, F. R. Banks, C.B., O.B.E., F.R.Ae.S. (The First Louis Bleriot Lecture).

The Elements of the Buckling of Curved Plates, H. L. Cox, M.A., F.R.Ae.S., and E. Pribram, D.E., A.F.R.Ae.S.

Correspondence.

Reviews.

CONVERSAZIONE—29th OCTOBER 1948

The Society will hold a Conversazione on Friday, 29th October 1948 from 8.0 p.m. until midnight at the Science Museum, South Kensington, by kind permission of the Director, Dr. H. Shaw.

The President, Dr. H. Roxbee Cox, D.I.C., F.R.Ae.S., F.I.Ae.S., and Mrs. Roxbee Cox, will receive members and their guests. During the evening aeronautical films will be shown and, for those who wish to dance, dance music will be played.

Tickets, including Buffet, will be £1 1s. 0d. each (£2 2s. 0d. for a double ticket). FOR GRADUATE AND STUDENT MEMBERS OF THE SOCIETY ONLY, the price of a double ticket will be £1 11s. 6d.

A distinguished company will be present and the President and Council hope that members and their friends will make a special effort to attend.

Application for tickets must be made on the form enclosed with the September Journal and Monthly Notices. Early application is advisable.

ANGLO-AMERICAN AERONAUTICAL CONFERENCE 1949

Arrangements are now being made by the Institute of the Aeronautical Sciences and the Society for the Second Anglo-American Aeronautical Conference, which will be held in America in the late spring of 1949. Full details of the programme and arrangements will be published as soon as possible. Members who propose to attend should inform the Secretary.

SOCIETY OF BRITISH AIRCRAFT CONSTRUCTORS' EDUCATIONAL GRANTS

The following Candidates were successful in the recent Educational Awards made by the Society of British Aircraft Constructors:—

University Scholarships

Mr. A. H. Eldridge (A. V. Roe & Co., Ltd.), to the College of Aeronautics.

Mr. D. L. Lofts (de Havilland Engine Co.) to the City and Guilds College.

Mr. J. E. Hart (Boulton Paul Aircraft, Ltd.) to the College of Aeronautics.

Mr. C. Faulkner (Saunders-Roe, Ltd.) to the College of Aeronautics.

Educational Grants

Miss J. A. Rowland (Amy Johnson Scholarship) to be apprenticed to the English Electric Co., Ltd.

Miss M. O. Legg, already employed as a Technical Assistant in the Aerodynamics Department of Vickers-Armstrongs, Ltd., Supermarine Works, will continue her training with the Company.

Mr. D. J. Leahy (Sir Nigel Norman Scholarship) to be apprenticed to Vickers-Armstrongs, Ltd., Weybridge.

LECTURE PROGRAMME—AUTUMN SESSION 1948

Unless otherwise stated, lectures will be held at 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, London, S.W.1 (by permission of the Council of the Institution). Tea will be served at 5.30 p.m.

Thursday, 30th September 1948

Fourth British Commonwealth and Empire Lecture.

Some Economic Factors in Civil Aviation, with Emphasis on Civil Aircraft and their Prospective Trends of Development, by Peter G. Masefield, M.A., F.R.Ae.S., M.I.Ae.S., G.Inst.Mech.E.

Wednesday, 6th October 1948

Some Aspects of Power Plant Development, by Dr. E. W. Still, B.Sc., A.C.G.I., A.F.R.Ae.S., A.M.I.Mech.E.

At the Chamber of Commerce, Birmingham, at 7.30 p.m.

Thursday, 21st October 1948

Cold Weather Operation of Aircraft, by G. W. Wilson, A.F.R.Ae.S., M.I.Ae.S., and Squadron Leader E. P. Bridgland, R.C.A.F., B.Sc., A.F.R.Ae.S., A.F.I.Ae.S.

Thursday, 28th October 1948

Aircraft Engineering and Production, by a Member of the Staff of Handley Page Ltd.

Saturday, 20th November 1948

FULL DAY DISCUSSION ON HELICOPTERS

(A Joint Meeting with the Helicopter Association)

Morning Session

11 a.m. to 1 p.m.—GENERAL PROBLEMS OF THE HELICOPTER FOR CIVIL USE.

11 a.m.—The Operational Point of View, by W/Cdr. R. A. C. Brie, A.F.R.Ae.S., A.F.I.Ae.S.

11.30 a.m.—The Technical Point of View, by Capt. R. N. Liptrot.

12 noon.—Discussion.

1 p.m. to 2.30 p.m.—Luncheon Interval (Members should make their own arrangements).

Afternoon Session

2.30 p.m. to 4.30 p.m.—THE CONSTRUCTORS' APPROACH TO THE PROBLEMS.

2.30 p.m.—The Fairey "Gyrodyne," by Dr. J. A. J. Bennett, D.Sc., M.A., D.I.C., F.R.Ae.S., F.Inst.P.

3.0 p.m.—The "Bristol 171" Helicopter, by R. Hafner.

3.30 p.m.—The Cierva "Air Horse," by J. S. Shapiro, Dipl.Ing., A.F.R.Ae.S.

4.0 p.m.—Discussion.

4.30 p.m. to 5 p.m.—Tea Interval. (Tea will be provided at the Lecture Hall.)

Evening Session

5 p.m. to 6.30 p.m.—General Discussion and summing up by the Lecturers and the Chairman.

Thursday, 25th November 1948

Development of the Armstrong Siddeley Mamba Engine, by W. H. Lindsey, M.A., A.F.R.Ae.S.

Thursday, 2nd December 1948

Problems in the Development of a New Aeroplane, by G. R. Edwards, M.B.E., B.Sc., F.R.Ae.S.

Thursday, 16th December 1948

Present Thoughts on the Use of Power Flying Controls in Aircraft, by D. J. Lyons.

GRADUATES' AND STUDENTS' SECTION

Lectures

***Tuesday, 28th September 1948**—Sailplane Design, by K. G. Wilkinson, B.Sc., A.C.G.I., D.I.C., A.F.R.Ae.S., British European Airways.

* *Provisional at present.*

Tuesday, 26th October 1948—Flight Refuelling, by Sir Alan J. Cobham, K.B.E., A.F.C., Hon.F.R.Ae.S., Managing Director, Flight Refuelling Ltd.

Wednesday, 10th November 1948—Flying Experiences, by Lt. Cdr. (A) E. M. Brown, O.B.E., D.S.C., A.F.C., M.A., A.R.Ae.S., R.N., Chief Naval Test Pilot.

Wednesday, 24th November 1948—The Investigation of Aircraft Accidents, by Air Cdre. Vernon S. Brown, C.B., O.B.E., M.A., F.R.Ae.S., Chief Inspector of Accidents, Ministry of Civil Aviation.

Tuesday, 7th December 1948—Papers read by members of the Graduates' and Students' Section.

Tuesday, 21st December 1948—Production, The Dynamics of People at Work, by J. V. Connolly, B.E., A.F.R.Ae.S., Professor of Aircraft Economics and Production at the College of Aeronautics.

Meetings will be held in the Library of the Royal Aeronautical Society, 4 Hamilton Place, W.1, at 7.30 p.m. *The Library will not be open before 7 p.m.*

Visits

Wednesday, 8th September 1948—Visit to the Ford Motor Company, Dagenham, Essex, at 2 p.m.

Saturday, 25th September 1948—Visit to Northolt Airport, Ruislip, Middlesex, at 10.30 a.m.

Members of the Section wishing to take part in these visits should write to the Hon. Secretary, Michael C. Campion, 6a Mildenhall Road, Clapton, E.5.

BRANCH NOTICES

COVENTRY BRANCH

Thursday, 16th September 1948—Rocket Flight (M.O.S. Film).

Thursday, 21st October 1948—Development of the Brabazon I, by G. P. Hebden, Bristol Aeroplane Co. Ltd.

Thursday, 18th November 1948—Electronics, by Dr. Whiteley, British Thomson-Houston Ltd.

Thursday, 9th December 1948—Lecture by E. Smith, Research Department, Firth-Vickers Ltd.

Thursday, 20th January 1949—Development of the Mamba Engine, by W. H. Lindsey, Armstrong Siddeley Motors Ltd.

Thursday, 17th February 1949—The London-Sydney Air Route, by C. H. Jackson, B.O.A.C.

Thursday, 17th March 1949—The Automatic Pilot, by A. I. O. Davies, Smiths' Aircraft Instruments Ltd.

Thursday, 28th April 1949—Annual General Meeting and Film.

All lectures will be held in the Old Gulson Library, Coventry, at 7.30 p.m.

GLASGOW BRANCH

Tuesday, 28th September 1948—A Film Evening, at 7.30 p.m., at Prestwick Airport.

Thursday, 28th October 1948—Lecture by a Branch Member, at 7.30 p.m., at The Grand Hotel, Charing Cross, Glasgow.

Tuesday, 30th November 1948—" Lecturettes," at 7.30 p.m., at Prestwick Airport.

Thursday, 23rd December 1948—Annual General Meeting, at The Grand Hotel, Charing Cross, Glasgow.

GLOUCESTER AND CHELTENHAM BRANCH

Thursday, 30th September 1948—Trend of Jet Engine Development, by A. A. Lombard, Chief Designer (Projects), Rolls-Royce Ltd.

Thursday, 18th November 1948—Problems Facing Civil Air Operations, by N. E. Rowe, C.B.E., F.R.Ae.S.

Meetings will be held at the Wheatstone Hall, City Library, Brunswick Road, Gloucester, at 7.30 p.m.

HATFIELD BRANCH

Wednesday, 13th October 1948—Aircraft Photography, by John Yoxall.

Wednesday, 17th November 1948—Design Problems of Large Flying Boats, by H. Knowler, F.R.Ae.S.

Wednesday, 12th January 1949—Blind Landing Technique, by J. W. F. Mercer, B.Sc., A.C.G.I.

Wednesday, 16th February 1949—The Probable Role and Influence of Aircraft in Future Warfare, by Air Marshal Sir Robert Saundby, K.B.E., C.B., M.C., D.F.C., A.F.C.

Wednesday, 16th March 1949—Annual General Meeting.

All Meetings will be held at 6.15 p.m. in the de Havilland Senior Staff Mess.

ISLE OF WIGHT BRANCH

Friday, 15th October 1948—Inaugural Dinner.

Thursday, 11th November 1948—" Lecturettes "—Four short talks by members of the production staff of Saunders-Roe, Ltd.

Thursday, 2nd December 1948—The Development of the Armstrong Siddeley " Mamba " Engine, by W. H. Lindsey, M.A., A.F.R.Ae.S.

Thursday, 16th December 1948—Annual General Meeting and Film Show.

Thursday, 20th January 1949—Aircraft Design from the Airline Point of View, by C. Dykes, M.A., M.Sc.

Thursday, 3rd February 1949—The Probable Role and Influence of Aircraft in Future Warfare, by Air Marshal Sir Robert Saundby, K.B.E., C.B., M.C., D.F.C., A.F.C.

Thursday, 24th February 1949—Naval Aircraft, by Lt. Cdr. (A) E. M. Brown, R.N., O.B.E., D.S.C., A.F.C., M.A., A.R.Ae.S.

Thursday, 10th March 1949—It is hoped that Mr. N. E. Rowe will present a paper.

Thursday, 24th March 1949—Debate.

Meetings will be held in the Sports and Social Club, Saunders-Roe, Ltd., East Cowes, Isle of Wight, at 6 p.m.

LUTON BRANCH

Wednesday, 6th October 1948—Accident Investigation, by Air Commodore Vernon Brown, C.B., O.B.E., M.A., F.R.Ae.S.

Wednesday, 20th October 1948—Presidential Address by the Branch President, P. Ll. Hunting, Comp.R.Ae.S., and Discussion Evening.

Wednesday, 3rd November 1948—Materials of Aircraft Construction and Material Processing, by Dr. Sutton.

Wednesday, 1st December 1948—The Light Aeroplane and the Future of Private Flying, by P. G. Masefield, M.A., F.R.Ae.S.

Meetings will be held generally at The George Hotel, Luton, at 7 p.m.

PORTSMOUTH BRANCH

Friday, 24th September 1948—Flight Refuelling, by C. H. Latimer-Needham, F.R.Ae.S.

Friday, 22nd October 1948—Lighter-than-Air Craft, by Lord Ventry, Companion R.Ae.S.

Friday, 26th November 1948—Model Section Display.

Friday, 3rd December 1948—Films showing " How an Aeroplane Flies."

Friday, 17th December 1948—Some Aspects of Carrier Operation, by Capt (E) B. H. Cronk, D.S.C., R.N.(Retd.).

Friday, 14th January 1949—Rocket Propulsion, by A. V. Cleaver, A.R.Ae.S.

Friday, 11th February 1949—Short papers by members of the Branch.

Friday, 11th March 1949—The " Debunking " of Aeronautical Science, by C. G. Grey, F.M.R.Ae.S.

All lectures will be held in the Lecture Hall at the Central Library, Guildhall Square, Portsmouth, at 7 p.m.

WEYBRIDGE BRANCH

Wednesday, 15th September 1948—Presidential Address by the Branch President, G. R. Edwards, M.B.E., B.Sc., F.R.Ae.S., A.M.I.Struct.E., and Discussion Evening.

Wednesday, 6th October 1948—Rocket Propulsion and Inter-Planetary Flight, by A. V. Cleaver, A.R.Ae.S., de Havilland Engines Co. Ltd.

Wednesday, 27th October 1948—High Speed Wind Tunnels, by E. J. Richards, M.A., B.Sc., A.F.R.Ae.S. and E. Smyth, B.Sc., A.F.R.Ae.S., Vickers-Armstrongs Ltd. (Weybridge).

Wednesday, 17th November 1948—Some Aspects of Practical Flying, by J. K. Quill, O.B.E., Vickers-Armstrongs Ltd. (Supermarine).

Wednesday, 1st December 1948—The Island Campaign (Coloured film), shown by W. Courtenay, M.M., A.R.Ae.S., *Daily Graphic* Aeronautical Correspondent.

Wednesday, 15th December 1948—Annual General Meeting, followed by films of Vickers Aircraft.

Friday, 28th January 1949—Annual Dance, Oatlands Park Hotel.

Wednesday, 9th February 1949—Civil Air Transport, by P. G. Masefield, M.A., F.R.Ae.S., Ministry of Civil Aviation.

Wednesday, 9th March 1949—Air Force Requirements and their Origins, by Air Commodore G. W. Tuttle, C.B., C.B.E., D.F.C., Director of Operational Requirements.

Wednesday, 30th March 1949—Junior Prize Lecture, by a Branch Member.

Wednesday, 27th April 1949—Present-Day Problems in Safety Requirements, by W. Tye, O.B.E., B.Sc., F.R.Ae.S., Air Registration Board.

Wednesday, 18th May 1949—Historical Review of Aircraft Development, by Sir Frederick Handley Page, C.B.E., F.R.Ae.S.

Meetings will be held at Vickers-Armstrongs, Ltd., Weybridge Works, at 6 p.m., unless previous notice is given.

BADEN-POWELL MEMORIAL PRIZE

The Baden-Powell Memorial Prize, awarded to the best candidate in the Associate Fellowship Examinations of the Society, has been awarded to Mr. A. Powell, Student Member of the Society, as a result of the June 1948 examinations.

ASSOCIATE FELLOWSHIP EXAMINATIONS

Candidates for the December 1948 examination are reminded that entries must be received by the Secretary by 30th September 1948.

The new Syllabus comes into force on 1st January 1949, but papers will continue to be set in the present syllabus up to, and including, December 1949.

The following Candidates were successful in the Associate Fellowship Examinations held in June 1948:—

HOME

Adler, F. B., Applied Mathematics; Aretz, J., Pure Mathematics.

Barford, N., Pure Mathematics, Design (Aircraft); Barnard, R. J., Theory of Machines; Barton, H. C., Applied Mathematics, Strength of Aeronautical Materials and Structures, Design (Aircraft); Biermann, G. T., Applied Mathematics; Birkie, J. W., Pure Mathematics; Theory of Machines, Aircraft Instruments—Theory and Design; Bryer, D. W., Theory of Internal Combustion Engines; Bunting, J., Theory of Machines; Bunting, W. H., Applied Mathematics.

Cash, R. F., Theory of Internal Combustion Engines; Challender, R. S., Pure Mathematics; Chaplin, J. B., Pure Mathematics, Aerodynamics; Charter, G. B., Air Transport; Cocheme, J., Meteorology and its Application to Aeronautics; Constantine, A. F., Pure Mathematics, Strength of Aeronautical Materials and Structures; Corkill, T. N., Design (Aircraft); Course, K. W., Pure Mathematics, Theory of Internal Combustion Engines; Currey, N. S., Aerodynamics.

Davis, J. L. (Miss), Design (Aircraft); Dixon, E. D., Aircraft Materials; Drayton, F. A., Applied Mathematics; Duncan, J. R. (Miss), Aerodynamics; Dymond, P. R., Strength of Aeronautical Materials and Structures.

Eccles, D., Pure Mathematics, Theory of Machines; Edwards, P. A., Design (Aircraft).

Farish, W. L., Applied Mathematics; Fuller, J. R. D., Theory of Internal Combustion Engines; Ferguson, J. F., Applied Mathematics; Furlong, O. D., Applied Mathematics; Fussell, A. L., Pure Mathematics, Theory of Machines, Wireless Telegraphy and Telephony and their Application to Aeronautics (1st Place).

Gallimore, P. L. E., Strength of Aeronautical Materials and Structures, Design (Aircraft); Ghose, N., Applied Mathematics; Green, G. K. F., Pure Mathematics.

Hammond, A. R., Applied Mathematics, Theory of Machines; Hands, C. P., Aircraft Materials; Harradine, P. J., Pure Mathematics, Strength of Aeronautical Materials and Structures, Aerodynamics; Harris, J. P. (Miss), Pure Mathematics; Harris, L. H. W., Air Transport; Hayward, D. W., Pure Mathematics; Heaton, W., Applied Mathematics (Tie 1st Place), Theory of Internal Combustion Engines, Design (Aero Engines); Howard, H. T., Aerodynamics; Hunt, D. I., Strength of Materials, Design (Aircraft).

Jackson, K., Applied Mathematics; Jelly, R. F., Applied Mathematics, Theory of Machines; Johnson, F. A., Pure Mathematics.

Keebie, J. B. E., Aerodynamics.

Lambert, J. A. B., Pure Mathematics; Langley, C. D., Strength of Aeronautical Materials and Structures; Le Lohe, M. P., Strength of Aeronautical Materials and Structures.

McCloghry, T., Theory of Internal Combustion Engines, Design (Aero Engines) (1st Place); McLaughlin, P., Applied Mathematics; Macpherson, W., Applied Mathematics; Mitra, K. K., Applied Mathematics; Morgan, H. H., Theory of Internal Combustion Engines; Morley, C., Pure Mathematics, Strength of Materials, Design (Aircraft).

Pardoe, G. K. C., Pure Mathematics (1st Place), Strength of Aeronautical Materials and Structures, Aerodynamics; Pathak, J. C., Applied Mathematics; Peddie, H. L., Strength of Aeronautical Materials and Structures; Petts, F. C., Applied Mathematics; Popkin, C. P. S., Applied Mathematics (Tie 1st Place), Theory of Internal Combustion Engines; Powell, A., Pure Mathematics, Strength of Aeronautical Materials and Structures (1st Place), Aerodynamics (1st Place).

Reid, J., Applied Mathematics; Rosenthal, J., Applied Mathematics.

Saben, E. W., Design (Aircraft); Sandeman, G. P. (Miss), Design (Aircraft); Schaetzel, S. S., Pure Mathematics, Strength of Aeronautical Materials and Structures, Aerodynamics; Simpson, D. M. S., Strength of Aeronautical Materials and Structures; Singh, H. P., Pure Mathematics; Smith, S. H. P., Theory of Machines (1st Place), Applied Mathematics, Srivastava, G. N., Pure Mathematics.

Terajewicz, J., Pure Mathematics, Strength of Materials, Aerodynamics; Tharratt, C. E., Applied Mathematics; Thompson, A. M., Strength of Aeronautical Materials and Structures, Design (Aircraft); Thorpe, J. B. J., Pure Mathematics, Theory of Machines, Aircraft Instruments—Theory and Design (1st Place); Thurston, B. O., Pure Mathematics; Toone, R., Pure Mathematics, Strength of Aeronautical Materials and Structures, Aerodynamics; Tudor, J., Applied Mathematics; Tweed, P. E., Applied Mathematics, Design (Aircraft).

Uydens, A., Pure Mathematics.

Vincent, D. W. R., Applied Mathematics, Theory of Machines.

Wade, R. P., Applied Mathematics, Strength of Aeronautical Materials and Structures; Bell-Walker, J., Applied Mathematics, Theory of Machines; Walker, C. H., Applied Mathematics; Walmsley, J., Theory of Internal Combustion Engines, Aircraft Materials (1st Place); Walmsley, J. H., Theory of Machines; Walters, P. D., Aerodynamics; Watkins, J., Applied Mathematics; Watson, N. S., Pure Mathematics, Strength of Aeronautical Materials and Structures, Theory of Machines; Wilson, D. F., Air Transport (1st Place).

ABROAD

Andrews, C. G. (Wellington, New Zealand), Applied Mathematics.
Bunyard, V. R. (Port Elizabeth, South Africa), Applied Mathematics.
Crowley, C. (Calgary, Canada), Aircraft Materials.
Dietiker, G. (Calgary, Canada), Pure Mathematics, Aircraft Materials.
Lamothe, R. F. (Calgary, Canada), Aircraft Materials.
McNeill, H. J. (Calgary, Canada), Pure Mathematics, Strength of Aeronautical Materials and Structures, Aircraft Materials; McKnight, F. H. (Calgary, Canada), Pure Mathematics, Strength of Aeronautical Materials and Structures; Mathur, J. N. (Bombay, India), Aircraft Materials.
Rao, S. K. (Bangalore, India), Design (Aircraft) (1st Place); Roper, M. R. (Wellington, New Zealand), Applied Mathematics.
Sumbler, C. C. (Calgary, Canada), Pure Mathematics, Strength of Aeronautical Materials and Structures, Aircraft Materials.
Taylor, C. R. (Cpl.) (B.A.F.O.), Aerodynamics, Meteorology and its Application to Aeronautics; Treleman, L. M. (Calgary, Canada), Pure Mathematics, Aircraft Materials (1st Place).
Willard, B. (Cpl.) (R.A.F. Changi), Applied Mathematics.

SECTION A

The following were the successful candidates in Section A of the Associate Fellowship Examination held in June 1948:—
Lewis, W. M., Elementary Mathematics, English; Sanderson, D. M., English; Thompson, R. G., Elementary Mathematics, English.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.
When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership.
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

NEW MEMBERS

Associate Fellows

Lewis Roland Barrett, John Albert Beard (from Graduate), Reuven Benzwi (from Graduate), John Laurence Bright (from Associate), Fred Paul Bruce, William Henry Burdon, Henry Busen-Schmitz (from Associate), Thomas Dorian Robertson Carroll (from Associate), Harold Thomas Chapman, David Mostyn Davies (from Graduate), David John Day, Wilfred Hubert Dukes, Eric Oliver Dummer (from Graduate), Reginald Wiliam Dunn, Ronald George Fall, Alan Edgar Foster (from Graduate), Jack Arthur Froude (from Graduate), Zygmunt Funt, Ivor Edward Giles (from Student), Eric Martin Goodger (from Associate), Raymond Walter Frank Gould, Cyril Grantham, Ronald Albert Charles Hallett, John Douglas Hamilton (from Graduate), Lily Kathleen Harrison, Geoffrey Bryan Hewitt, Sidney Greville Higgins, David Siegfried Holmes (from Associate), Thomas Arthur House, Harry Brynmor Hughes, Owen Lewis Hyde (from Student), James Jackson, Thomas Edmund Johnson (from Associate), John McPherson, Sydney Herbert Masters, Henry William Newman, George William Nunn (from Associate), Donald Pierce (from Graduate), George Frederick Pitts (from Student), Manfred Pohoryles, Leslie Alex Guy Reeve, Antony Horrex Richardson, Richard Charles George Thomas Rogers (from Associate), Herbert Derrick Ruben (from Graduate), Arthur Clarence Sanderson (from Graduate), James Antony Hosking Sargeaunt, Alan Sharpe, S. Gopalakrishna Shivshankar, Albert William Edward Stanley (from Associate), Donald Bull Swinbanks (from Graduate), Eugeniusz Szomanski, Maung Kyaw Tha, Henry Charles

Baden Thomas, Donald Watson Tripp (from Associate), Hugh Wason Turner (from Graduate), Peter Hayward Wall (from Graduate), Bernard John Watson (from Associate), Edward Weiser, George Albert Willis (from Associate), Cecil Solomon Wills, Robert Norman Wimshurst, Joseph Woodward (from Associate).

Associates

Allan Noel Norman Abbott, Henry William Adams, Hugh Adams, George Aubrey Allen, John Edward Atkins (ex Associate), Roland Shirley Austin, William George Ayres, John Edward Baker, Alan Beaton, Arthur Douglas Bentley, James Robert Booth, Harold Edwin Braithwaite, Lewis Charles Budd, Leonard George Burnard, Ivor Jenkins Cadwallader, John Frederick Carrington Carrington, Hector Catlow, Gerald Arthur Champniss, George William Chirgwin, Leonard Edwin Swaffield Cowan, Geoffrey Hugh Docker, Horace William George Donkin, Geoffrey Dorman, Ernest George Faulkner, Edmund James Galpin, Charles Joseph Thomas Gardner, Adam Rutherford Gourlay, Clifford Graham-Jones, Charles Cyril Graves, Edward Gregory, Cecil Charles Head, Philip Charles Heming, Leonard Francis Hubbard, Herbert Charles Humphreys, Leslie Donald Kent, Trevor Fleetwood Lawrence, James William McCombie, John McDonald, Harold Stanley Martin, Derek Mason, Edward Harry Maule, Jocelyn George Power Millard, Thomas Victor Nelson, Desmond Henry Clements Nixon, Maxwell Norman Oxford, Frank Reginald Parker, Brian Stanley Pittaway (from Student), Tom Ernest Pratt, Henry Shawbrook, James Patrick Spillane, Donald Lee Taylor, Leslie William Norman Walker, Reginald George Warne, Eric Michael Welch, Joseph Thomas White, David John Williams, John Augustine Wren.

Graduates

John Russell Baxter (from Student), Guy Bransby Charter (from Student), John Waterston Furness, Peter Michael Gray (from Student), Richard Francis Harrison, Michael Alaric Josselyn Morton Hayward, Ralph Spenser Hooper (from Student), John Dudley Lewis, John Reighcraft Purchase (from Student), Edward Albert Ridge (from Student), Dennis John Tyler.

Students

William Allan Chapman, Ronald Arthur Cole, John Noel Critchley, Alexander William Houston, Gordon Eric Monger, John Gordon Hedley Pearce, Hamid Sapru Riaz, James Velkou, James Henry Wilson.

Companions

Biren Roy.

ACKNOWLEDGMENTS

The Council acknowledge with grateful thanks gifts of books from J. Bateman, Esq., Associate, Mrs. Kronfeld and W. A. Woodward, Esq., and back numbers of the Journal from J. R. Lander, Esq. (ex-Student), J. D. L. Stratton, Esq., Associate Fellow, and T. E. Voss, Esq. (ex-Student).

ADDITIONS TO THE LIBRARY

Pamphlets in italics with location reference following in brackets. Books marked * or ** may not be taken out on loan.

A.c.18—Applied Thermodynamics. Robinson and Dickson. Pitmans. 1948.

BB.b.136—Fundamentals of Aircraft Structures. Millard V. Barton. Prentice Hall. 1948.

BB.b.137—Elementary Structural Analysis. J. B. Wilbur and C. B. Norris. McGraw Hill. 1948.

BB.b.138—Aeroplanes and Aero-Engines in Detail. J. H. Clark, L. Cresswell, W. J. Everest and T. Page. *The Aeroplane*. 1948.

BB.c.110—Theory of Propellers. T. Theodorsen. McGraw Hill. 1948.

BB.f.70—Aircraft Instrument Maintenance. E. F. Werner. McGraw Hill. 1948.

BB.f.71—Electronics Instruments. I. A. Greenwood, J. V. Holdam and D. Macrae. McGraw Hill. 1948.

BB.g.1—Sampling Inspection. H. A. Freeman and others (Editors). McGraw Hill.

D.b.276—Wings around the World. B. W. Leyson. Dutton. 1948.
EE.b.93—Aircraft Engines of the World. P. H. Wilkinson. P. H. Wilkinson. 1948.
EE.j.45—Aviation Catalogue. Engineering Data and Handbook. Weatherhead Co. Cleveland, Ohio. 1944.
K.c.32—Rocketry; Jets and Rockets. C. P. Lent. Pen-Ink Ltd. 1947.
L.d.123—*Notices to Airmen. Nos.* 251-255, 257-261, 263-268, 270-286.
L.d.124—Loran Long Range Navigation. J. A. Pierce, A. A. McKenzie, R. H. Woodward (Editors). McGraw Hill. 1948.
L.d.125—Instrument Flying. Weems and Zweng. Weems System of Navigation. 1947.
M.b.56—Computing Mechanisms and Linkages. Antonin Svoboda. McGraw Hill. 1948.
*X.c.B.32—Scientific and Technical Abbreviations and Signs and Symbols. O. J. Zimmerman and Irvine Lavine. Industrial Research Service. 1948.

N.A.C.A. Technical Reports

752—*On a new method for calculating the potential flow past a body of revolution. Carl Kaplan.*
759—*Derivation of charts for determining the horizontal tail load variation with any elevator motion. H. A. Pearson.*
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Report No. SM 107.

British Intelligence Objectives Sub-Committee
F.I.A.T. Final Report No. 873.
B.I.O.S. Miscellaneous Report No. 83.

State Institute for Technical Research, Finland
Report No. 1.

National Luchtvaartlaboratorium, Amsterdam.
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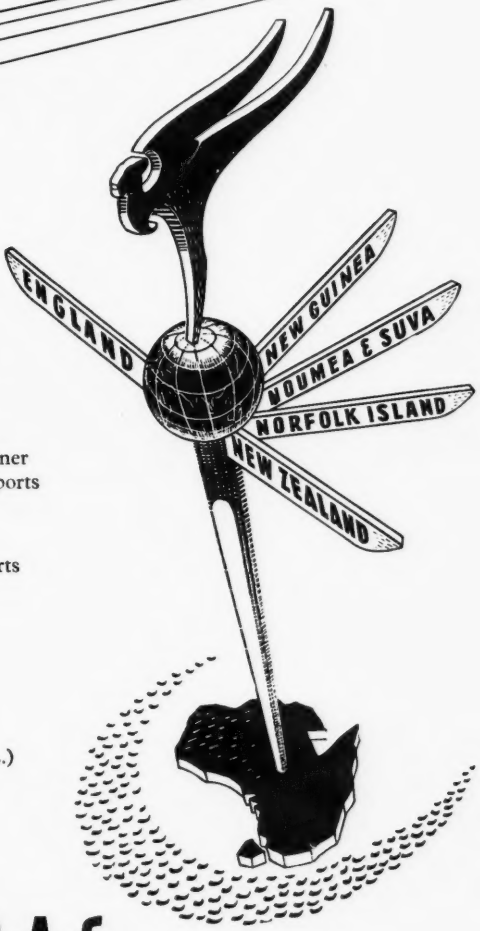

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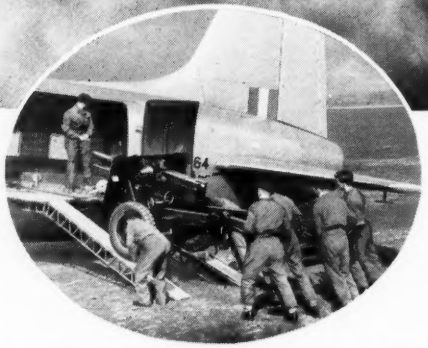

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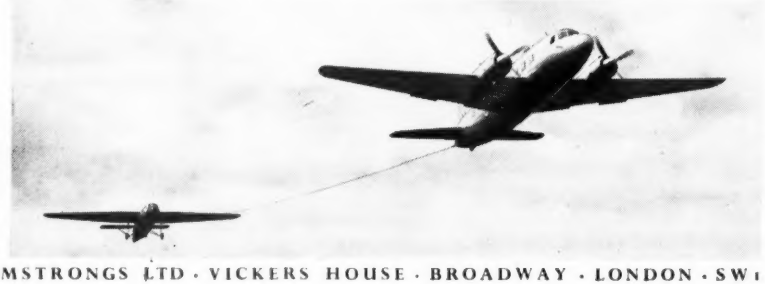

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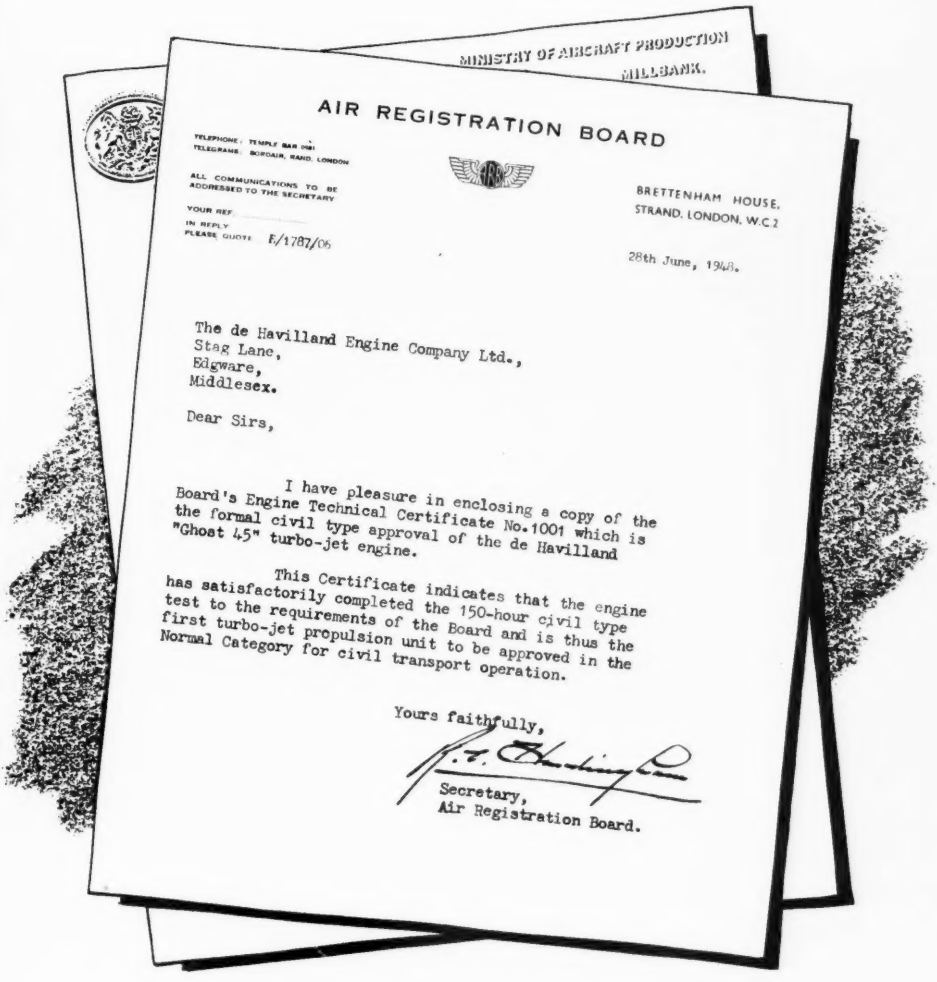

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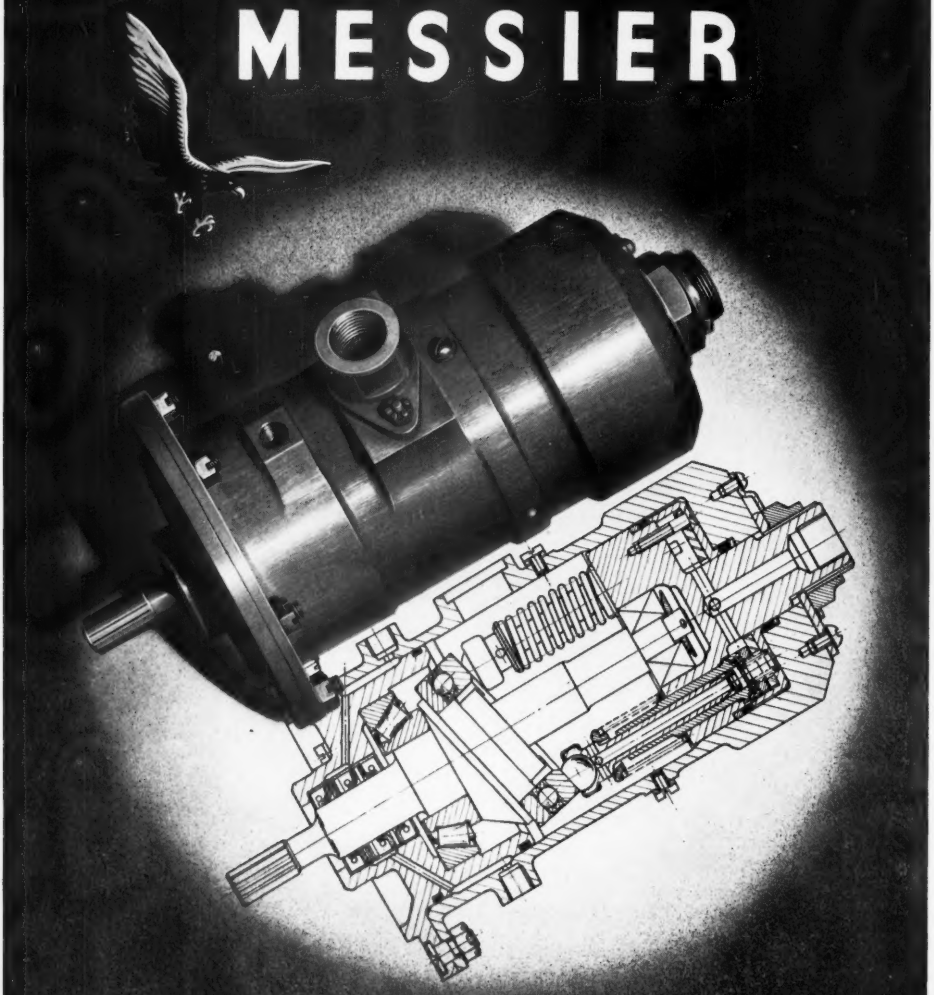

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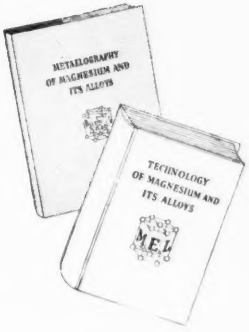

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THE ART OF THE AVIATION ENGINE

by

F. R. BANKS, C.B., O.B.E., F.R.Ae.S.

To commemorate the great French pioneer Louis Bleriot, who made the first crossing of the English Channel by aeroplane on 25th July 1909, the Association Française des Ingénieurs et Techniciens de l'Aéronautique, better known as A.F.I.T.A., has instituted a series of lectures to be known as The Louis Bleriot Lectures. The Lecture is to be given annually and the intention is that it should be given alternately, in Paris and London, by an Englishman and a Frenchman.

The first Louis Bleriot Lecture was given in Paris on 12th May 1948, in a lecture hall attached to the Hotel George V, by Air Commodore F. R. Banks, C.B., O.B.E., F.R.Ae.S., M.I.Mech.E., F.I.Pet. It was attended by the President of the Royal Aeronautical Society, Dr. H. Roxbee Cox, D.I.C., F.R.Ae.S., F.I.Ae.S., Sir Frederick Handley Page, C.B.E., F.R.Ae.S., Past-President, the Secretary, Captain J. L. Pritchard, Hon.F.R.Ae.S., F.I.Ae.S., and by a number of members of the Society and of the Aircraft Industry.

Monsieur Jules Jarry, President of A.F.I.T.A., presided over the meeting. Introducing Air Commodore Banks, he welcomed the representatives of the Royal Aeronautical Society and spoke warmly of the help which A.F.I.T.A. had received from the Society and its President. He referred to a previous paper which had been given by Air Commodore Banks to A.F.I.T.A. and expressed the Association's gratitude to Col. Guy du Merle, Director of Technical Development at the French Air Ministry, who was to read the paper in French on behalf of Air Commodore Banks.

Dr. Roxbee Cox, President of the Royal Aeronautical Society, speaking in French, referred to the friendship between France and Great Britain and how appropriate it was that that friendship should be strengthened in their aeronautical communities and that the new series of Lectures should commemorate the name of the man who had first linked their two countries by air.

He expressed his own and his colleagues' appreciation at being present on this great occasion and their pleasure that for the first lecturer A.F.I.T.A. had chosen Air Commodore Banks, who was well-known in both their countries and for whom they had respect and affection. On behalf of the Council and members of the Royal Aeronautical Society he thanked A.F.I.T.A. for their invitation to be present on this great occasion, which they hoped would be the first of a number of successful meetings.

He also expressed his pleasure at announcing that two members of A.F.I.T.A., M. René Lucien and Colonel Guy du Merle, had been elected Fellows of the Royal Aeronautical Society.

Air Commodore Banks apologised, in French, for not reading his paper in that language and paid tribute to Mr. Michael Golovine for translating his paper and to Colonel Guy du Merle who was to read it for him.

The First Louis Bleriot Lecture. Given before the Association Française des Ingénieurs et Techniciens de l'Aéronautique, in Paris, 12th May 1948.

Air Commodore Banks is Technical Manager and Chief Engineer of The Associated Ethyl Co. Ltd.

INTRODUCTION.

THIS is a very special occasion for me and I deeply appreciate the honour done me, an Englishman, in being asked to give the first Louis Bleriot Lecture. I hope that it will initiate a long series of lectures honouring that great man of French aviation and, in so doing, will also acknowledge the very important part played by France in world aviation.

It is the second occasion upon which I have been honoured by an invitation to deliver an address and it gives me great pleasure again to meet my French friends of the A.F.I.T.A.

I was very young when Louis Bleriot flew the Channel, but I always remember the excitement I experienced when the London newspapers acclaimed this great feat and when I went to see the machine on exhibition. Now, 39 years later, man has flown non-stop for a distance of more than 18,000 Kms. (11,000 miles) and has exceeded a speed of 1,000 Kms.-hr. (600 m.p.h.). But none of these things would have been achieved without the efforts, perseverance, ingenuity and bravery of the pioneer pilot-constructors like Bleriot. To these men—all honour.

Previous papers of mine and by others have dealt with the working principles and specialist problems of the aviation engine, but no one has yet described how this type of engine is conceived and developed to the state of series production; nor has it been understood why some manufacturers are more successful than others in this respect.

When, therefore, I was asked by the Association to present another paper, I decided that, in view of the importance of the occasion, the time had arrived to describe the evolution of the aviation engine.

THE AVIATION ENGINE AND OTHER PRIME MOVERS.

The internal combustion piston engine has been used in aviation for more than 40 years; indeed, flight would not have been practicable without it.

Since our experience to date has been entirely built up on the piston engine, it will form the basis of this lecture.

The intrusion and early success of the gas turbine has undoubtedly altered the piston engine's future in aviation, but it may well be that the piston engine will continue indefinitely in aviation for certain purposes and particular applications. Certainly, it will be used for many years for private aircraft and for the smaller feeder line machines, also for moderate speed and low level reconnaissance aircraft and other similar types. In other words, and contrary to the original thoughts on the gas turbine, it does not appear now that this new prime mover can completely take the place of the piston engine for all purposes. But it will certainly do so in the high power, high duty class.

A particular feature which distinguishes the aviation engine from all other forms of prime mover, is that it must meet a stringent weight limitation and, at the same time, produce high power from small volume. The steam railway locomotive and the marine engine, for example, are not required to work at high specific output, but must operate for long periods before overhaul becomes necessary. Their weight and size are not, therefore, so critical.

Another important difference is the relative lack of finality in aviation; here the development of the aeroplane and its engine is never static, but always progresses towards the attainment of still better performance.

The demands made upon the aviation engine have always been exacting and are not likely to be any easier in the future. This is particularly true at the present time of the aviation gas turbine—an entirely new form of prime mover now in its infancy, which must be subjected to the same intensive development as the piston engine before it can be considered to have attained the equivalent state of refinement.

An aviation engine only dies when its basic design does not permit further practical or economic improvement in performance, or when the aeroplane in which it is fitted is rendered obsolete; then, it must be discarded for an entirely new design and the whole development process started again.

A successful engine type will last for about ten years, and sometimes longer, during which time it will be developed and modified in the form of many improved "Marks" before the basic design is discarded. This is an important factor and its significance will be better appreciated as the lecture proceeds.

The total running life of an individual engine in airline service varies considerably with operating conditions, and is also controlled by the size of engine and whether or not it represents a relatively new type.

The term "life" is difficult to define because at each period of overhaul or revision, the

engine will be brought to its original standard of quality by any replacements which are necessary. In other words, many of the components may be renewed in successive overhauls, including that part to which the original engine name plate and number are fixed, usually the crankcase. Even if the crankcase has to be replaced, the original engine number is often transferred to the new case, thus preserving the identity of the engine for many more hundreds, or thousands, of hours. It will be appreciated, therefore, that it is difficult to give a realistic or practical definition for the life of an engine.

Individual airline engines are finally written off and condemned to the scrap heap after a complete or catastrophic failure, or if the engine overhaul period is shortened because of more frequent replacements of certain components; and if it becomes uneconomic to replace some of the more expensive components at each period of revision. Therefore, the operating life of an individual airline engine is likely to vary considerably, and may be anything from 3,000 to 12,000 hours before the engine is discarded.

Some of the more moderate duty types of American engine of about 30 litres cylinder capacity, which have been in airline service for over ten years, have achieved a total working life, per engine, as high as 20,000 hours.

It has been the practice in Great Britain, between the two World Wars and since World War II, to adapt high duty military engines for airline use. But, at the beginning of the recent war, only one specific type of engine, the air-cooled radial, had been consolidated as an airline engine. Now, both liquid and air-cooled engines are in use on British airlines.

For those directly interested, there is an interesting article, published in the Bulletin of the American Society for Testing Materials (No. 148, October 1947), which gives some valuable information on airline engine maintenance. The title of the article is "Cutting Aircraft Engine Maintenance Costs," by E. A. Droegemueller.

In the article, it is mentioned that American airline organisations overhaul or revise about 25 per cent. of their total engines (including spare engines) every month. And a major American airline will overhaul as many as 1,000 engines in a year.

The utilisation factor, which represents the useful running time per year for an engine, or an aircraft, including overhauls or revisions, will average about 3,000 hours.

A well-developed aviation engine will run for at least 750 hours and, even, 1,000 hours on airline service, between overhaul periods or revisions. Either figure is a good target for the gas turbine, when it eventually comes into regular use.

As a matter of interest, and for contrast, the life of a steam railway locomotive is about 33 years, and the railway companies consider this period to be the "legal" limit for safe operation in service. Locomotives require boiler cleaning and washing out every two weeks, inspection and overhaul of wheels and crankshafts or axles and so on, at about 112,000 Kms. (about 70,000 miles), and a major repair of the boiler is usually made at 240,000 Kms. (150,000 miles).

But, by comparison, the distances represented by the running times of 750 and 1,000 hours for the aviation engine are not inconsiderable. Assuming a moderate cruising speed of 300 Kms./hr. (186 m.p.h.), these are 225,000 and 300,000 Kms. (140,000 miles and 186,000 miles), respectively.

The thermal efficiency of the aviation engine is greatly superior to that of the steam locomotive; more than four times better. The former has a (brake) thermal efficiency of about 30 per cent. at a cruising condition of approximately 50 per cent. of its take-off power, but the latter has an efficiency of little more than 6 per cent. on the average run, although a figure of 8 per cent. has been achieved on specific journeys.

The Diesel or compression ignition heavy oil engine, which is now coming into general use in America for locomotives hauling long-distance passenger trains, could also be cited as another example and one which might be considered a better comparison with the aviation engine than the steam locomotive. Its thermal efficiency is, of course, comparatively high, being between 28 and 30 per cent., on "the rail."

The following information which I obtained from the principal manufacturer of American Diesel-electric railway locomotives, will be of considerable interest. As in the case of the steam locomotive, there is nothing exactly comparable with the normal maintenance of an aviation engine, but the following data shows that this type of engine has reached a very high state of development.

The piston rings, which control the first major maintenance period, have an average life of about 1,000,000 Kms. (about 620,000 miles) in passenger service or, approximately, 22,000 hours. Next, in order of those parts requiring attention, are the pistons. These are changed after running for the equivalent of 1,600,000/2,000,000 Kms. (1,000,000/1,250,000 miles) or 37,000 hours. The pistons will not show serious wear in this period, nor are they likely to have excessive ring groove clearance, but they are discarded for safety reasons, because of the danger of thermal stress fractures. The cylinder heads and valves also operate for approximately the same period. The connecting rod and main bearings have an operational period of about 2,400,000 Kms. (about 1,500,000 miles), or 45,000 hours.

It is stated that little is known about the average life of the major components such as the crankshaft and the camshaft, but this is estimated to be considerably in excess of 6,400,000 Kms. (4,000,000 miles) or approximately 150,000 hours. No engine has yet run to the limit of crankshaft life, because other parts have required attention or replacement much before this period. All these figures are most impressive.

THE AVIATION ENGINE IS BORN.

Before the first World War, when aviation was in its infancy, a number of French engines of original design came into being. These were responsible for the success of French aeroplanes of that period; and the names of Antoinette, Anzani, Gnôme, Clerget, Le Rhône, Renault and Salmson, and so on, became famous and made aviation history.

Aviation engines were also being built in other countries. There were the Green, E.N.V. and Aster in England and the Benz and Austro-Daimler in Germany and Austria, and so on and so on. In the very early part of this century (1901), in America, Manly designed and built an extraordinarily advanced engine which was far ahead of its time. Unfortunately it was not continued, principally because of the lack of an aeroplane in which to fly it. Then came the Wright brothers' engine, which proved to be one of the most reliable of the early engines.

There were other engines produced in the various countries, but I have only mentioned those which actually made flying practicable.

The Seguin brothers conceived the rotary Gnôme engine, which was the lightest of its time. It was of relatively low specific power output, but its ingenious operating principle permitted very light construction.

The Antoinette engine employed gasoline injection, and the only reason for the lack of reliability of this system was entirely due to the fact that it was many years in advance of its time and the necessary engineering knowledge and technique were then lacking.

In the early part of the War of 1914-18, the French Gnôme engine was used with success. It was also built by the British and by the Germans. Then, in 1916, came the famous Hispano engine, which helped to direct the air war in favour of the Allies. The Hispano was built in quantity in England and also in America.

Later, in the same war, Rolls-Royce produced the first outstanding British aviation engines, the Eagle and the Falcon. These engines were both outstanding in performance and reliability. Two other successful British engines were, the Bentley (rotary) and the B.H.P. Puma.

Towards the end of the war a new British engine, the Napier Lion, was designed and built. The Lion represented a further step in higher power output and, although it was not produced until after hostilities had ceased, it became a famous engine in the post-war Royal Air Force. At about the same period, the Royal Aircraft Factory (now the Royal Aircraft Establishment) which was responsible for the R.A.F. engine (largely of Renault pattern) during the war, designed a static air-cooled radial engine. This was later taken over by the Armstrong-Siddeley Company and became known as the Jaguar. It was virtually the prototype of the modern radial engine and, in its original design, had the first mechanically-driven supercharger.

After the 1914-18 War, a number of the original engine firms disappeared for various reasons. But, in England, between the two World Wars, the successful line of Bristol engines was born and Rolls-Royce followed their famous Eagle and Falcon with the Condor, Kestrel and Merlin engines. In France, during this period, there remained Hispano. Then the Gnôme et Le Rhône Company was formed, building the Bristol Jupiter under licence and, later, designing and building their own engines. There was also, the Lorraine.

There were, in France and Great Britain, other engine manufacturers which I have not

mentioned, but it is my purpose here to present briefly only the highlights or peaks of aviation history of the two countries, as a prelude to later remarks.

In the recent and second World War, the Merlin engine made aviation history and was used for both fighters and bombers. No other engine was so versatile or so popular. It saw service in many "Marks" or types throughout the war, from 1939 to 1945. Later in the war, Rolls-Royce produced the Griffon and, still later, the Eagle (reviving a famous name), but the latter did not see war service.

Rolls-Royce also developed and produced the Derwent and Nene jet turbines during this period.

The Bristol Mercury and Pegasus engines, which were developed from the Jupiter, also gave good war service, to be followed by the Taurus and Hercules sleeve-valve types. The Hercules engine gave excellent war service in bombers and night fighters. Later still came the Centaurus.

The Napier Company designed and built the Sabre, which was used in the war. They had previously developed and built such engines as the Javelin, Rapier and Dagger, but the Sabre was their most outstanding engine after the Lion.

In a period of more than forty years of aviation, the power of the individual engine has increased from 35 h.p. to more than 3,500 h.p. And the altitude at which sea level power can now be maintained has risen from sea level, to more than 10,000 metres (30,000 ft.).

THE STATUS OF THE AVIATION ENGINE.

The aviation engine industry, which was born in the first World War, is unique as an industry because it flourishes mainly as the result of national support. This is distinct from nationalisation, with which it should not be confused. Unlike the traditional armament business the aviation engine industry has useful application in peace; but it enjoys Government support because of the military potentialities of the aeroplane.

The principal reason why this support is necessary for the existence of a healthy industry is one of finance, caused by the enormous cost of developing an engine, the almost catastrophic consequences if the engine fails to be accepted, and the relatively small production orders in peace time, if the engine is successful. It is, therefore, difficult to justify the investment of sufficient capital without promise of Government orders.

Another important reason is that every new engine, in its prototype form and in the early production "Marks," generally owes its existence to the military requirements of the particular country in which it is built. Rarely does an engine become useful, say, for civil airline operation until it has first seen some military service. Indeed, unless a new engine can start its life in airline service and operate for 350 or 400 hours between revisions, the operating and maintenance charges become excessive. Even this period of operation is too short and there is little profit until a running time of about 750 hours has been attained. This will involve at least three years of regular flying on the air routes and demand complete co-operation between the engine manufacturer and airline operator in attending to troubles as they arise, without delay.

With a new military aeroplane, risks are justified which cannot be tolerated in passenger aircraft. It is, therefore, permissible to take reasonable risks and fly an engine in its early development stage, in order to build up experience rapidly. Also, in peace time, it is not of such great consequence if a military aeroplane is grounded because of engine trouble and modification. But an airline must be able to operate without major engine trouble and all the subsequent delays incurred.

Therefore, an entirely new type of engine will first meet military requirements and then have at least two years of military service, to ensure a reasonable degree of reliability before it is considered for airline use.

When an engine is chosen for service in a civil transport aircraft, the engine manufacturer should endeavour to run hangar tests of long endurance, reproducing as closely as possible all the operating conditions likely to be met on the airline route, or routes. The engine will be operated as a complete power plant, the replica of that intended for the aircraft.

When the aircraft itself is ready, it will be delivered to the "development flight" of the particular airline concerned, after the aircraft manufacturer's tests and final performance tests by the civil aircraft licensing authorities. The personnel of the development flight will then fly it on the route, or routes, without passengers but, perhaps, with freight in order to judge the behaviour of the aeroplane and

engine. The carriage of freight will help to defray development costs. It may take more than a year to complete the flight development of a new aeroplane and its engine, before it is satisfactory for carrying passengers, equivalent to 800 or 1,000 flight hours.

It is still the opinion of some that an engine should be designed specifically for airline use. But, in the present state of the art and for reasons previously mentioned, it is not financially or technically advisable to do this. Such a policy would tend to produce a relatively large and heavy engine, because of the high cost of development which could not be fully borne by the manufacturer, who, in consequence, would apply a further safety factor in the form of a power limitation, in order to ensure a reliable engine with the minimum of development cost.

The acceptance of a basic military type for airline operation can sometimes result in a medium capacity, highly developed engine being chosen which, later, proves to be too small for further economical improvement in performance and, therefore, has restricted application. However, the choice of a suitable engine is largely a matter of experience and foresight in assessing future engine availability when the design of the aeroplane is being considered.

I have already indicated that the aviation engine represents very specialised engineering and I will emphasise this further by saying that other organisations, such as those which build steam turbines or large Diesel engines, do not easily acquire that entirely different technique and outlook. The ordinary industrial firm, even though it may be well staffed with capable technicians, could not successfully mix the two types of engineering. This would only be possible by complete separation and the formation of a special section entirely devoted to the design and construction of aviation engines, but it would take about ten years to obtain successful results.

Automobile firms might be more capable of learning aviation engine technique than the heavier engineering concerns. But the "Shadow Group," comprising the major automobile companies in Great Britain, which did excellent work during the recent war and produced many thousands of aviation engines, would be the first to admit that their particular ability was to organise for the production of an engine which had already been developed by the parent firm. They would not claim to have the "know-how" enabling them to design and develop the engine, prior to production.

I have stated that, if a country desires a healthy aviation engine industry, it must be prepared to give support in a practical manner. But it is also necessary to formulate advanced technical requirements if superior engines are to be built.

It is not usually appreciated how few active aviation engine companies there are in the world to-day. The total number of firms manufacturing high duty engines barely exceeds fifteen, excluding Russia, Germany and Japan. At the present time in any of the countries claiming to have an aviation industry, there are only about two or three engine manufacturers who have production orders in addition to their State supported development work. In the present condition of world aviation, if all of these (fifteen) firms were producing at full output, they could make more engines than could possibly be required for military and civil purposes in peace time.

It will be seen, therefore, that the aviation industry is, or should be, competitive. But advantage is too often taken of the fact that it enjoys Government support and some firms are inclined to sit back and wait for orders, with little apparent incentive or energy to design and build advanced engines.

The number of really active firms who are building successful engines to-day can almost be counted on the fingers of one hand.

Such a state of affairs is generally due to lack of foresight on the part of the firms in question. Often, they have been too satisfied with the success of an earlier engine and failed to see what must follow it; with the result that a competitor has anticipated them by producing a more advanced type.

This has happened many times in the past, particularly when the creation of a successful engine depended, more than it does now, upon an individual designer of good engineering ability, and one who was also possessed of a sixth sense, permitting him to "crystal gaze" into the future and see what was wanted. With the accumulated experience which most of the established firms have to-day, and because of the greater technical knowledge required, the whole business of making aviation engines is becoming more a matter of organised team work, involving a considerable degree of specialisation.

The most important single factor in building aviation engines is that of timing. It is of little use to have a superior design if the subsequent development of the engine is slow. There have been many cases where an engine of promising design has not found a market because of another engine which has been developed more quickly. The question of timing in this industry cannot be overstressed.

An aviation engine firm should be controlled by experienced engineers, preferably those who have worked up through the various levels and sections and who possess administrative ability and sound technical judgment. Firms have failed in the past because, although they had engineers in control, these men had lost interest in the technicalities of the work to force the pace for the personnel under them; indeed, they held them back. It is most important that, under the senior men in any firm, there should be younger men who have been chosen for their technical knowledge and administrative ability, to take the place of their seniors when the latter retire.

Again, when things have gone wrong because of technical inadequacy, some companies have come under the direct control of bankers and accountants. When this happens, all is lost. Bankers and accountants are necessary for the creation and running of any organisation but, unless they are very understanding people—which is not usual because they lack engineering knowledge— they can wreck a firm more quickly than any engineer if they interfere with technical policy. They have been, in the past, good sponsors and servants of the aviation industry, but are generally their poor masters.

THE EVOLUTION OF THE MODERN AVIATION ENGINE.

The highest form of engineering art is represented in the manufacture of the aviation engine, but scientific and technical aids are necessary for its consummation.

I have often been asked to define the difference between "research" and "development," when applied to the aviation engine. In my opinion there is no difference, but when the term "research" is used it should be prefixed by "applied" or "objective." In fact, most research in industry is applied or objective, because it must always be limited by the factors of time and practical application, unlike pure research which is undertaken in order to increase our knowledge of the happenings in the Universe and to find reasons for particular phenomena. Pure research is not restricted by time, nor do the results necessarily have any immediate practical application.

Therefore the terms "research" and "development," as they are used in this lecture, will be synonymous.

A successful engine results only from sound basic design combined with intensive development. A good basic design is of great consequence and will save many valuable hours of testing and of "making and breaking," always an expensive process in man-hours, material and money. An enthusiastic and energetic technical staff, which has at its disposal all the necessary testing facilities, supported also by an adequate and flexible manufacturing department, will quickly overcome many of the deficiencies which are inevitable in a new engine.

The designer is always in close touch with the experimental and manufacturing sections. He will have all the results of the experimental work and be informed immediately of any failures which occur. It is only by this process that he can design out of his troubles and prevent the recurrence of failures.

The designer will also be in close contact with the production department in the early stages of the engine's design and, particularly, in the later stages of its development, in order that the production engineers can give advice on the practical and economical production of the engine.

There is, however, a most important proviso to the liaison between the technical (design and experimental) sections and the production department. It is that the technical people must have the final decision in the case of any argument between them and the production department, as to the suitability of the design of the engine or its components for production. In other words, design must not be subordinated to production considerations if, as the result of experiment, the engine and all its parts operate well. But, at the same time, the design and technical sections must be fair and should not face the production people with unnecessary complication. If they ignore the production aspect the result may recoil on them; because a complicated part, which is difficult to manufacture correctly, will delay the production of the engine and add to its cost.

This may appear to be a statement of the obvious, but it is extraordinary how often manufacturing and even functional difficulties occur because of lack of proper co-ordination between the technical and production staffs. At the same time, it is also remarkable what the production people can do in making parts of complex design when they try! But an engine in its infancy and early development should not be prejudiced by too rigid production considerations; in any case, it is difficult to judge at that stage what the final form of a component and its details will be.

In times of peace, an aviation engine firm is virtually one large development organisation. The production department, which is distinct and separate from the experimental section which machines and manufactures the prototype engine and its components, is relatively small in capacity. The large experimental and prototype machine and assembly shop capacity, at first sight, might appear somewhat wasteful. But, unless an engine can be rapidly dismantled and rebuilt, with any new components which may be necessary, its development will be delayed; and it is demoralising to the experimental staff when there are no engines to test. It is usual to work night shift, in the machine and assembly shops, on components which are urgently needed.

I have often judged the vitality of a firm by the degree of activity on the test beds. Nothing is so disheartening as the dead silence of test beds without engines; and when this is still apparent after two or three regular visits, it is obvious that there is something radically wrong with the firm in question. This rarely occurs in a well-organised firm. To run an engine is always necessary, even if the reason is apparently trivial; because the experimental staff must get all the experience possible and learn what they can of the engine.

Experience has shown that the time taken to design, develop and get the first, or "Mark I," version of a prototype piston engine into production is between four and five years.

An exception to this was the Rolls-Royce Griffon engine, which was designed and built during the recent war and went into production in about three and a half years from the initial design stage. But the design of the Griffon followed well-tried lines and, although it had a larger cylinder capacity than the Merlin, its basic design was similar. It also incorporated a number of lessons learned as a result of the long life of the Merlin and its intensive development.

The increasing use of test rigs for the separate development of components, such as the supercharger, has helped to shorten the time taken to get an engine into production; in the case of a piston engine of conventional design, this might now be nearer four than five years.

It is not expected, however, that any engine of entirely new design, whether it is of the piston type or is a gas turbine of the axial compressor variety, will take much less than five years to progress from its original conception to the start of production.

In the present state of knowledge this is particularly true of the propeller turbine, which needs an equal, if not longer, experimental period before it reaches the type test stage and can be put into production. Even the turbo-jet with an axial compressor will take little less time to develop.

Many people thought that the turbo-jet could be designed, developed and produced very quickly; and their views were apparently further strengthened when, during the recent war, Rolls-Royce designed and built the prototype Nene and Derwent V turbo-jet engines and gave them the first run on the test bed, each in less than six months. But these engines represented the simplest form of turbo-jet, in which were incorporated certain already well-tried features. The gas turbine with the axial compressor is a much more formidable undertaking, and rapid development of this type of engine must not be expected.

The design of a gas turbine involves many more serious and protracted mathematical calculations than are required for the piston engine. Perhaps, later, when more is learned of the aerodynamic and thermodynamic problems of the gas turbine, as the result of further development and long practical experience, it may be possible to reduce the time of development, because of the greater degree of finalisation possible in the design stages, by more complete calculation. But, in my opinion, this will not be possible for some years to come.

TEST RIGS.

All the principal engine manufacturers have a special section devoted entirely to the testing of the individual engine accessories; that is to say, those accessories which help

to function the engine and those which are functioned by the engine for the aircraft equipment. Although these accessories are usually proprietary articles made by reputable firms, they have to pass an individual and official type test before they can be certified as suitable for an engine. But it is most important that the engine manufacturer also satisfies himself as to the suitability of a particular accessory for his engine. Therefore, the usual practice is first to calibrate such items as the fuel pump and magnetoes, and so on, and then give them endurance tests, on rigs driven by electric motors.

The accessories which are driven by the engine, but whose purpose it is to operate airframe equipment, include vacuum and hydraulic pumps, electric generators and, where specified, the cabin air conditioning compressors, and so on.

After they have been rig tested, the accessories are fitted to the engine and undergo bench tests and, later, flight tests. It is good practice to keep a new accessory in operation on an engine for some hundreds, and even thousands, of hours in order to ascertain its actual life and the degree of reliability to be expected in normal service. This also applies to the accessory drives and couplings, which continue to be a source of weakness and failure. Naturally, the accessories and their drives will not always remain on the same engine, but will be transferred to other engines in order that their running may be continued.

The effect of engine operation on the accessories, or *vice versa*, and the influence of the power and torque variations and vibration stresses, excited either by the engine or its accessories, is most important. Many failures of an engine component, an accessory, or a drive coupling, have been traced to the "incompatible marriage" of an accessory with the engine, even though each functioned well when operating separately.

The reliability of the complete engine is only as good as that of its accessories and their drives, all other things being equal.

GOVERNMENT CONTRACTS.

As stated already, to maintain a healthy aviation engine industry, Government orders or contracts are necessary and the Government Department must also formulate advanced requirements of high technical merit. But there is a most important point for this Department to consider when it invites tenders with the intention of later placing contracts. This concerns the terms upon which a tender will be accepted and a contract awarded; and it can influence to a significant degree the final and practical result, and largely controls whether or not a successful engine will emerge.

Normally, Government contracts are awarded to ordinary industrial firms on the basis of the lowest cost or, even, a fixed price tender. Although this system is sometimes satisfactory when related to equipment such as automobiles, trucks, stationary diesel, or gasoline engines and, even, steam turbo-generators, and so on, it is not at all satisfactory when applied to the aviation engine.

The peculiar nature of the aviation engine demands that each tender must only be considered on its technical merit and the capability of the firm concerned to develop the engine to type test standard, in a reasonable time. For instance, a firm may submit a promising design, but their past history will indicate that the development of the engine is likely to be slow.

One method of judging the capacity, if not the capability, of a firm to execute a contract in reasonable time, is to obtain from them an estimate of the man-hours required to design and build the prototype engine, together with a statement of the capacity available; this will also include details of the testing facilities. Naturally, this does not allow for the important factors of "energy" and "brains." Therefore, the past history and the successes or failures of the firm must also be known. The ability of a firm to spend money rapidly will often give some idea of its potentialities. A firm that can usefully spend £2,000,000 in one year, on development, will produce an engine more quickly than one which requires two or three years to use the same amount. Mature consideration and long experience, on the part of the Department or Ministry, are necessary when assessing the capabilities of the various firms.

If a firm is slow or ineffectual in doing its development, it is sometimes suggested that the design should be acquired by the Ministry and then given to another more capable firm. But this will not always ensure getting a successful engine, because it is only human nature for one firm to dislike giving a promising design to another. And there will certainly be a lack of enthusiasm on the part of the original design staff, who may already

have further advanced ideas for the future of their engine.

All this brings into focus the question of the personnel and staffing of Government Departments or Ministries, whose duty it is to consider and formulate the particular requirements. Some countries favour military personnel (officers) in control of the various technical sections, with permanent civilian staff under them in order to preserve continuity when the former return to their Service duties and other officers take their places. In other cases, civilians only are employed to control and staff the technical sections.

Both systems have their advantages and disadvantages. In the former case, the military or Service personnel bring into the sections an atmosphere of realism, since they are the practical users of the equipment. But it is difficult for an officer to appreciate the technical implications of the work in the engine section of a Ministry. Even if he has had some previous technical training this is not usually sufficient for him to understand all the technicalities, because he probably lacks practical engineering experience. Also, it is the normal practice in most military Services to appoint an officer to a position for a limited period of three years and often less. Since it takes a qualified engineer many years to gain his experience and become proficient, officers must have under them experienced and permanent civilian personnel, if their sections are to work efficiently and produce results. Continual changes of personnel have a bad effect on efficiency and, therefore, some system should be evolved which will allow officers to remain in their positions for at least five years, and longer, if they are particularly suitable.

The forward progress of aviation and the exceedingly high performance military aircraft promised for the future suggests that the period of active piloting will tend to become more limited and, after the age of, say, thirty years, or less, an officer will cease to be of full value as a military pilot. This is a frightening thought and, even in recent years, the relatively short active term of the military pilot has caused considerable uneasiness among the pilots themselves and some anxiety to the Air Staffs, since air force recruiting is not encouraged in these conditions.

It is evident that officers, after completing their relatively short term of active flying, cannot all become Generals or Air Marshals, but they must be usefully employed. Therefore, they should be carefully selected and trained to fill administrative and technical posts. Some will have the natural ability and inclination to take responsible positions in the aviation engine section.

It matters little, in my opinion, if the engine or other technical sections are controlled by officers or civilians, but they must be good administrators of some technical ability.

CONTRACTS.

Reverting to the important question of contracts: when a contract is awarded to a firm, it will usually confirm the manufacturer's original tender and price for designing and building a prototype engine, plus any additional engines which have been agreed between the firm and Ministry, for the various aircraft in which the engine is to be fitted. The aircraft, themselves, may also be prototypes.

As a general rule, the engine manufacturer will require eight or ten engines for his own bench tests, plus two or three additional engines for flight tests. The number required for prototype aircraft will depend upon the type of aircraft. On the basis of a single-engined pursuit type, two engines will be wanted, *i.e.* one for the aircraft and one spare engine. But, since experience has shown that military aircraft usually have to perform in different roles and with alternative equipment, it is also the normal practice to order a number of the prototypes. One aircraft will be wanted for flight performance tests and another will be required by the armament section for firing trials. Further machines will be needed if it is also intended to use the type for ground attack and high speed photographic reconnaissance and similar duties.

It will be appreciated, therefore, that at least sixteen engines must be included in the contract, *i.e.* ten for the engine manufacturer, three for aircraft and three spares.

In the case of multi-engined aircraft, it is usual to estimate spare engines on the basis of fifty per cent. of the number of engines fitted in the aircraft, making the quantity ten for the engine manufacturer, as before, and multiples of four plus two for the aircraft manufacturer, in the case of a four-engined aircraft.

The engine manufacturer may not immediately prepare to make the engines ordered

for the prototype aircraft, but will first wait until the prototype engine has reached a stage of development where major or drastic modifications are unlikely to be required. This is to avoid waste of valuable man-hours and material. For the same reason, he will often only complete about three or four of the ten engines required by himself, and will keep the equivalent of six engines in the form of forgings, castings and semi-finished parts.

The contract price and conditions will make provision for an acceptance test of the first prototype engine, at a previously declared power. The conditions of the acceptance test will vary according to the type of engine and whether its design follows well-tried lines, or if it is entirely original. In the former case, the test conditions may demand one or two hours of running on the test bed at a pre-determined percentage of the engine's maximum rated power, *i.e.* fifty per cent. or even full rated power. If the engine is of original design and represents completely new practice, then the test will only be of a nominal nature, consisting of a run of about half an hour on the test bed at, say, half engine speed and at a fraction of its maximum power.

The sole purpose of the acceptance test is to give practical proof to the Government Department or Ministry concerned that the engine has been built and, in fact, exists. It is in the nature of a qualifying test, which then allows the firm to proceed with the development of the engine at Government expense. It can be compared with the case of the new pilot who has just obtained his "brevet" or "wings"; these are symbols only of his qualification, which afterwards permit him to obtain further experience in his profession.

After the acceptance test and when the engine has been stripped and examined by the inspectors of the Ministry and the firm, the manufacturer can then request a further contract for x number of hours of development testing. It is British practice to issue separate contracts for building the prototype engine and for its subsequent development. The latter contract can be extended, or a fresh contract granted, if further running is required as the result of difficulties experienced during development.

For example, a manufacturer will request a contract for 500 hours of experimental running on the test bed at an agreed rate of, say, £100 per hour. This will include the stripping and minor modification of the engine but, if a major failure occurs which demands a radical re-design, the firm can apply to the Ministry for a separate contract for the re-design and manufacture of the particular components. In the meantime, the running contract is kept in abeyance until the engine is again ready for test.

The cost of test bench running will vary from £50 to £100 per hour, according to the size of engine (single cylinder or full-scale) and the nature of the tests to be run.

A number of single cylinder units of the full-scale engine will be built, well in advance of the full-scale engine. Their running is usually the subject of separate contracts, but the principal running contract for the full-scale engine may be granted on an omnibus, or inclusive, basis and an overall hourly rate agreed with the Ministry. If the full-scale engine has an unusual cylinder arrangement, some of these units may be built to represent a section of the full-scale engine with the cylinders arranged accordingly, *i.e.*, if the engine has the cylinders opposed, some units will be built with two opposed cylinders.

The crankcase, crankshaft and all other parts of a single cylinder unit, with the exception of the cylinder and piston which, naturally, must represent those of the full-scale engine, should be of very rugged construction. A great waste of time can be caused by any breakages not directly concerned with the components that are being tested.

The contract procedure described here is mainly representative of British practice, and the whole secret of success in Government contracting lies in the technical honesty of the firms concerned, and the benevolent control exercised by the Ministry. There must always be mutual trust between it and the firms, in order that they are not restricted in their efforts to make better engines.

This freedom of control extends to the selection of the materials of construction. An engine manufacturer may use what he considers the most suitable material for a particular component but any such material will have to be finally approved by the Government Agency, when the engine passes type test and goes into production.

INSPECTION.

The inspection department of an aviation engine firm should be under the control of the Chief Engineer, who is in full technical

control of all departments, including that of production, and is responsible for the final quality of the engine.

For some years, it has been British practice for the A.I.D. (Aeronautical Inspection Directorate) to grant all reputable firms official approval of their own inspection departments and, although the A.I.D. retain resident inspectors at the firms, they are there principally to advise and to arbitrate when necessary. To be an "approved firm" is to place that firm upon its honour to maintain an inspection department which will be a credit to the organisation and will maintain no less a standard of quality than would be demanded by the A.I.D.

The A.I.D. inspectors, however, remain responsible for observing all acceptance and type test procedure. This includes the preliminary inspection of the engine and its test equipment, the type test running and the subsequent inspection of the engine and its accessories.

I could expand further on the subject of inspection, but time and space are limited and it is my sole purpose here to state the absolute necessity of an efficient inspection department and to emphasise that it must be under the control of the Chief Engineer. The production department obviously should not be responsible for its own inspection.

Actually, there will be two separate inspection departments; one for production engines and one for experimental engines.

ORGANISATION AND WORKING CAPACITY.

The organisation of a firm should be as simple as possible, and those who are to take charge of departments and sections must be carefully chosen, and then allowed full responsibility for the control of their work and the personnel under them. The delegation of duties, by the Director of a Government Department (Ministry) or the Managing Director and the Chief Engineer of a firm, is to be encouraged because, if these officials have too much detail to attend to, they will not be able to give sufficient attention to important matters of policy. Their departmental managers will be in a better position to handle the details and this also develops in the latter a sense of responsibility which will be of particular value later, if and when the more important positions become vacant.

Great care must be taken to interpret correctly the meaning of organisation and what, in fact, organisation is. The recent war emphasised the necessity of organisation and planning in every field of activity, but they became much abused terms. What was often thought to be organisation was represented solely by a "genealogical tree" or chart purporting to show the departmental arrangement and functions which, in practice, did not always work because the Director attempted to do everything himself and missed a number of important matters in the process.

The organisation and planning mania has unfortunately persisted since the war and there is still a craze on the part of Governments and others to organise everything, almost to complete extinction. It is, therefore, with some diffidence that I submit, in Fig. 1, a chart giving my idea of the particular organisation necessary for an aviation engine manufacturing concern. Naturally, this would be considerably elaborated in practice, but the purpose here is to show the principal departmental arrangement, control and responsibilities.

The success of the organisation will depend primarily upon the factors just mentioned and the degree of flexibility, not rigidity, of the control exercised by the Managing Director and Chief Engineer; otherwise, the organisation chart becomes another "scrap of paper."

Since they are human, these officials may not at first choose the most suitable people for some of the particular positions, but they must be quick to see when a man is unsuitable and make the necessary change without too much derangement. In this connection, it is sometimes unwise to dispense with a man's services entirely, if he has not fitted the position. It is also unfair to the man if he has been taken from a position in which he has done well and put into another, perhaps of higher level, for which he is unsuited; because he will inevitably be judged a failure by his performance in the new position and all the good work he has done previously will be forgotten. Those with specialised knowledge of aviation engines should not be lightly discarded, because they are comparatively few in number and do not "grow on trees" or "in the fields." In any case, hasty dismissals always have a bad influence on the morale of an organisation.

Following the question of organisation comes that of the capacity of the firm, in

BOARD OF DIRECTORS
MANAGING DIRECTOR
CHIEF ENGINEER
COMPANY SECRETARY
STAFF & LABOUR MANAGER
PRODUCTION MANAGER
SERVICE AND AIRLINE LIAISON
CONTRACTS GOVERNMENT LIAISON
TECH. LIAISON WITH AIRCRAFT MANUFACTURER
BUYER
DESIGN OFFICE
DETAILING OFFICE
PROJECT OFFICE
EXP. PRODUCTION MANUFACTURING AND ASSEMBLY
MATERIALS TESTING DEPT
CHIEF INSPECTOR
PRODUCTION INSPECTION
EXPERIMENTAL INSPECTION
PRODUCTION DEPT
FIELD SERVICE
PRODUCTION ENGINE SPARE PARTS
REPAIRS AND MODIFICATION
PRODUCTION ENGINE TEST AND DISPATCH
SUB-CONTRACTS DEPT
PLANNING JIGS & TOOL PROGRESS MACHINE SHOP TOOL ROOM ASSEMBLY ETC ETC
METALLURGIST
CHEMIST
NON-FERROUS MATERIALS
FERROUS MATERIALS
PHYSICAL TESTS LABORATORY
CHEMICAL TEST OF FUELS, OILS, HYDRAULIC FLUIDS AND SLUDGES ETC
CHEMICAL TESTS OF SYNTHETIC RUBBER JOINTING MATERIALS, PLASTICS ETC
ENGINE INSTALLATION POWER PLANT FLIGHT TEST DEPT
EXPERIMENTAL ENGINE TEST SECTION
SINGLE CYLINDER TURBINE, FUEL PUMP INJECTION & COMBUSTION CHAMBER TESTS
RIG TESTS, ELECTRICAL & ELECTRONICS SECTION
FULL SCALE ENGINES TEST
ENGINE FLIGHT TEST
EXPERIMENTAL POWER PLANT & ENGINE INSTALLATION SECTION
PRE-PRODUCTION ENGINE DEPARTMENT
EXPERIMENTAL FOUNDRY PRECISION CASTINGS
DRAWING OFFICE POWER PLANT AND ENGINE INSTALLATION DESIGN
D.O. LIAISON — STANDARDISATION ETC.

FIG. 1.

terms of man power, to develop and manufacture engines quickly.

In connection with the total capacity or effort of a firm, it is assumed that, with the exception of proprietary accessories and so on, most of the engine will be manufactured within the organisation. It is most inadvisable to depend upon a large degree of sub-contracting and this should only be considered in the case of unusually large orders or, of course, in time of war, when the firm must expand beyond its normal limits.

If, however, it is necessary to resort to sub-contracting, then there is only one way to ensure satisfaction. The engine manufacturer should invite the sub-contractor's superintendents or foremen and inspectors responsible for the actual work to visit him, so that they may see for themselves the manufacturing process and the standard of inspection required. When the sub-contracting firm begins the production of the particular components, a representative from the engine firm should be stationed at the sub-contractor's works in order to give advice and to check the quality of the first samples to be made.

There is a minimum engineering capacity which is absolutely necessary for the proper and efficient functioning of an aviation engine factory regardless of immediate production considerations. It differs considerably in this respect from the more commercialised engineering industries. For instance, no other type of engineering concern could expect to maintain such large and comprehensive development facilities in relation to its production department. This, in terms of technical and operative man power, often appears unbalanced to the uninitiated, particularly in times of peace when only relatively small production orders are given.

But there is no substitute for "know-how"; which includes the sound basic design and intensive experimental work (the "make, test and break" technique) that must be done in order to produce, eventually, a reliable engine.

In Table I, I have shown my estimate of the minimum man power requirements, divided as to the relevant departments and sections. This gives only the number of personnel, technical and manufacturing, who are directly concerned with the creation of the engine. It does not include secretarial and clerical staff or the millwrights and labourers, and so on, all of whom are also indispensable to such an organisation.

The figures given in this Table are estimates, and are the result of my experience of the more successful aviation engine manufacturing organisations. The actual figures are not specific to any particular firm, but they are intended to give some idea of the relative proportions of the various departments, and of the organisation which must be built up, by experience and a moderate degree of success, to give a firm some chance of becoming seriously competitive.

Excepting item *I* (*b*) items *A* to *J*, inclusive, are all concerned with engine development and the total of technical, experimental and allied personnel is 2,697, say 2,700. This total will be subject to some variation, naturally, according to the number of prototype and other engines in process of development, but it should only alter very little at any time, because it represents the true assets of the firm, without which it is useless. A successful concern will have at least two different prototype engines in progress, together with a number of new versions or "Marks" of engines already in production, in various stages of development.

An analysis of the figures against some of the items in the Table may be helpful. The projects office and models section are usually directly under the control of the Chief Engineer and it is their business to think ahead on very advanced engine types. The models section will make small scale models of the engine and also of various possible aircraft installations. These are then judged on their practicability and attractiveness, and are sometimes used as wind tunnel models in order to assess their efficiency. They are not to be confused with the full-scale "mock-up," which is constructed preparatory to building the actual aircraft, to check cowling lines and installation details such as pipe and control runs.

In the case of *H*, this might appear to be a high figure but, if an engine installation and flight test department is to be efficient, then a relatively large number of maintenance personnel is always required for servicing the aircraft. It is important to fly as much as possible and, in Great Britain, the weather changes so quickly that regular test flying is almost impossible, certainly from the end of October until March. Therefore, every flight engine hour is very valuable indeed and poor

TABLE I.

	Department or Section	Number of Personnel Technical and Operative
A.	Project Office and Models Section	12
B.	Drawing Office—Design, Production and Modifications	400
C.	Experimental Manufacture, Fabrication, Assembly and Experimental Foundry	1,000
D.	Experimental Test Beds for Piston Engines and Gas Turbines	150
E.	Experimental Test Beds for Single Cylinder Units, Gas Turbine Combustion Chambers, etc.	30
F.	Metallurgical and Chemical Departments	30
G.	Rig Tests, Electrical and Electronics Sections	50
H.	Engine Installation, Power Plant and Flight Test Department	800
I.	Inspection Departments:—	
	(*a*) Experimental Engines	150
	(*b*) Production Engines	375
J.	Field Service Engineers (all grades)	75
K.	Production Engines—Machining and Assembly	1,500
L.	Production Engine Test and Dispatch	60
M.	Repair and Modifications Department for Production Engines; Stripping, Fitting and Reassembly	200
N.	Spare Parts Production	300
	TOTAL	5,132

maintenance and the resulting unserviceability cannot be tolerated.

Referring to item *I*, the total number of those engaged on production inspection represents one to every four production operatives, *i.e.* 375 inspection personnel to 1,500 operatives. A large proportion of the routine inspection staff are girl viewers, distributed throughout the various production sections.

The departments referred to in *M* and *N* are often merged into one, which then represents about thirty-three per cent. of the production department's working capacity, *i.e.* 500-1,500.

In times of peace and particularly at the present time with the advent of the gas turbine, which necessitates very large experimental and development facilities, about one-half to two-thirds of the total capacity, or effort, of a firm will be devoted to the needs of experiment and development. The proportion will obviously vary with the number of production engines ordered.

The production figure of 1,500 personnel is an arbitrary estimate and assumes a production rate of 1,000 engines per annum for a model which takes 3,000 man-hours to machine and assemble, ready for test. It also assumes present-day working hours of 40-44 per week or, roughly, 2,000 hours per man per year. This figure excludes personnel engaged in the various ancillary sections such as those for cleaning, enamelling, anodising, plating, and so on.

When the prototype engine has successfully passed the official type test, a number of engines are usually built by the experimental department, on a pilot or pre-production basis, ahead of the production programme and while the production department is tooling up. The number will vary according to the size of the principal order and the complexity of the tooling, but will be of the order of 25 to 50 engines.

DESIGN AND DEVELOPMENT.

Before the decision is taken to build an entirely new engine, there will be many discussions between the Chief Engineer and the heads of the project and design offices,

and with the aircraft designers and technical staffs of the Ministry.

As a result of these talks, various schemes for the engine and its installation in the aircraft will be submitted by the project engineer; models of the engine and the different installation arrangements will also be made.

It will be appreciated that the demand for the engine, in the first place, is generally the result of a provisional aircraft requirement which has been issued by the Ministry to the aircraft industry Since the engine takes longer to develop and produce than the aircraft, the Ministry will wish to have early information on the type of engine required, in order to place contracts for its design and development as soon as possible, and in advance of the aircraft contract.

It has already been stated that it is not wise to build an engine only on the assumption that some use will eventually be found for it. Therefore, it is important that the engine firm enjoys the confidence of the aircraft manufacturer who will, as the result of satisfaction in the past, favour the particular engine for his new aircraft. The complexity of the modern engine installation and the importance of a "clean" aircraft form will demand complete technical liaison between the two firms, and a good sense of timing, to obtain successful results.

The relationship between the design and production departments and whether or not an engine of inferior performance will be built if its design is subordinated to production considerations, has already been mentioned. But there are good reasons, particularly in time of war, for some attention to the question of production economy.

Take for example, the piston engine in the recent war: the most economical British engine built, in terms of manufacturing or man-hours, was the twelve-cylinder 60° V, liquid-cooled, poppet-valve type. The next in order of merit was the fourteen-cylinder sleeve-valve radial engine of about the same maximum power. The engine requiring the greatest number of man-hours in its manufacture was the twenty-four-cylinder, opposed type, liquid-cooled, sleeve-valve engine, with two crankshafts.

The actual manufacturing times for each of these three engine types was of the order of 2,200, 3,300 and 6,500 man-hours, respectively, at a production rate, per factory, of 400-500 engines per month. These figures exclude such items as the magnetos, spark plugs, ignition harness, carburettor and other proprietary accessories.

Later in the war, a larger 60° V-type twelve-cylinder, liquid-cooled engine was produced, which had the same cylinder capacity (36.6 litres) as the twin crankshaft, twenty-four cylinder, H-engine, just described. This engine was designed in close collaboration with the production department and the manufacturing hours were some 43 per cent. of the latter engine. But, as previously stated, production simplicity, or otherwise, must first be balanced by the potentialities of the engine's future and forward development, its performance and installational suitability.

There is one important factor which is not often appreciated. This concerns the ability and capacity of a firm to develop engines intensively. In other words, when buying an engine, it is power and performance which are actually being purchased; and the firm most active in the technique of development will produce better performance from an engine of given size, and weight, than another firm which may offer only the same performance from an engine of, say, twenty-five per cent. larger capacity. Therefore, intensive development always pays and, finally, leads to the production of engines of lower cost.

The information given here represents many years' experience of piston engines. Now, however, the gas turbine must be considered. Although only the relatively simple jet turbine, so far, has been manufactured on a production basis, there is sufficient evidence available to judge the cost and time trends of the more elaborate gas turbines, particularly the propeller turbine with the axial compressor.

The Whittle type jet turbine, with a double-sided, single stage, compressor and a single stage turbine wheel, giving a static, sea-level, thrust of 5,000 pounds, requires somewhat less manufacturing or man-hours than a 60° V-type, twelve-cylinder, liquid-cooled engine of about 2,500 h.p. take-off rating. But the jet turbine costs considerably more per pound of structure weight than the piston engine.

When comparing both types on the basis of horsepower, rather than thrust, the jet turbine appears attractive, in terms of specific cost (total cost/h.p.). But the comparison is deceptive and perhaps not very accurate, because the static or test bed performance of the jet turbine has little significance and must

always be related to the performance of the aircraft for which it is intended. It is, therefore, more accurate to compare both types on the basis of thrust.

The relatively high cost of the gas turbine is mainly caused by the special alloys used in its construction, *i.e.* for the combustion chambers, the stator and turbine blades and the turbine disc. It is difficult to foresee how this cost will be reduced in the future, since these alloys are composed of elements which would be in short supply if there were universally large gas turbine production. Lower grade and less costly materials could be used by reducing the working temperatures and stresses but, since the working efficiency of the turbine is already relatively low and the fuel consumption high, any further reduction in temperature could hardly be tolerated. Alternative materials will undoubtedly be sought and, if they prove only to be equal to the present high alloys, the element of competition may result in some reduction in the price of material. Ceramic coatings are being investigated, particularly in America.

This all represents long term investigation, or research, and quick results cannot be expected. In the meantime, the use of positive cooling for the turbine disc and blades would allow higher working temperatures with the existing high alloys, which would result in higher efficiency and, perhaps, show some improvement in the specific cost, *i.e.* better performance for nearly the same cost, or same total engine weight.

The design and manufacturing costs of a prototype gas turbine with a multi-stage axial compressor are also high. The number of blades used in this type of engine, including the compressor, stator and turbine blades, may total more than two thousand; and each compressor stage will have blades of different size and, perhaps, shape.

The present uncertainties in the design and performance estimates of the axial compressor are due to the lack of data available to the designer. This particularly applies to a compressor of advanced design. Therefore, at the present time, considerable trial and error testing of a compressor must be done in order to determine the best blade shape and arrangement. This is an expensive procedure, because every change in the design of the blade involves long calculation, after which the production of the new blades is slow and costly, because of their number and variety.

I do not subscribe to the opinion that the axial compressor type gas turbine will always be very expensive, or impracticable to build in large quantity. With more aerodynamic knowledge of blades and by running compressors having various blade designs and arrangements, sufficient data should be collected for a compressor to be designed which will not require too much alteration after it is built. Then, once the optimum blade design has been confirmed, it is not beyond the capabilities of the production specialists to produce blades accurately and in quantity. The extreme accuracy and almost super-finish required for each blade are additional factors which make it difficult to reduce costs for the relatively small quantities required at the present time.

The man-hours involved in the design and manufacture of a prototype propeller gas turbine, with an axial compressor, are from ten to fifteen per cent. greater than those needed for a large twenty-four-cylinder, twin crankshaft, liquid-cooled, sleeve-valve, piston engine, assuming the same maximum power for both engines, *i.e.* 3,500 h.p.

The cost of a prototype engine varies somewhat with its size, or maximum power, and complexity, but is between £10 and £20 per pound of structure weight. As an example, a large liquid-cooled piston engine of 3,500 h.p., maximum, which weighs 3,700 pounds, will cost about £15 a pound, or £55,000; and, perhaps, even more if it has twenty-four cylinders, sleeve-valves and two crankshafts. A propeller turbine of about the same maximum power will weigh much less, but will absorb more design hours and cost more per pound to manufacture in prototype form. Therefore, the total cost will be of the same order as that of the equivalent piston engine, assuming a weight of 2,900 pounds at £20 per pound, say £58,000.

About 80,000 man-hours are expended on the design and detailing of a large piston engine of about 3,500 h.p. and between 15,000 and 20,000 man-hours for a Whittle type jet turbine of 4,000-5,000 pounds static thrust. As mentioned previously, about fifteen per cent. can be added to the design time of the large piston engine for the design of an axial type propeller turbine of equivalent power.

Table I was constructed on the basis of a design and experimental capacity sufficient

to build one large prototype engine of, say, 3,500-4,000 h.p. (piston engine or propeller turbine) in eighteen months or two years. That is to say, a limit of two years from the start of design to the completion of an engine ready for its first test. At the same time, the project and design offices should be able to work on preliminary schemes for at least one further new engine, ready to follow the prototype after the design of the latter has been completed.

In addition, the drawing office capacity will be sufficient to deal with new versions or "Marks" of, say, two existing engine types which are already in production, plus all the designing and detailing for the modifications which attend such engines throughout their working life.

The principal factor controlling the speed at which a new engine is designed and built, ready for test, is the rate at which drawings are made and issued to the experimental manufacturing department. The liaison between the design office and this department, during the design stages of the engine, is most important.

Even before these drawings are issued, this department will have received sufficient information from the design office so that orders can be placed for material and some of the semi-finished parts, *i.e.* forgings and such things. Should the engine design incorporate a number of castings, it is of considerable advantage if the firm has an experimental foundry under its direct control; thus some of the more complex castings can be made and tested quickly, before ordering castings for the production of engines from outside sources.

In the case of a piston engine, it is most probable that the design of the supercharger will be completed in advance of the main components, such as the crankcase and cylinder blocks, so that it may be built and rig tested in order to determine its performance in readiness for the engine.

This will also apply to the compressor of a gas turbine, whether of the centrifugal or axial type, if there is sufficient power available. Early data on the performance of gas turbine compressors, particularly the axial variety, must be obtained because of the unknowns and the large amount of testing and redesign involved.

One section of the design office will design, in advance, a single-cylinder unit for testing the cylinder and piston assembly, particularly if the new piston engine is to have a different cylinder size to previous types. For a gas turbine, one of the design sections will be detailing the combustion chamber, so that one can be built quickly for the test rig to study its characteristics and to obtain a value for combustion efficiency.

For the gas turbine, it is also necessary to test the turbine wheel or disc to determine its factor of safety. This is done by rotating the disc (either hot or cold) in a vacuum at and above its maximum operating speed (r.p.m.) in a pit of special construction, mainly of reinforced concrete, lined with timber and lead of considerable thickness. In some of the American factories, small steam turbines are used for rotating the turbine wheel.

Factories possessing more elaborate equipment are also able to obtain a value for the efficiency of the turbine wheel, complete with its blading, by driving it with hot gas derived from a large auxiliary combustion chamber. Some firms, which have not this expensive equipment, make small-scale models of the turbine disc, with light alloy blades and drive them with cold air obtained from ordinary engine superchargers, on test rigs. Apparently, suitable corrections can be made which give reasonably accurate results when related to actual full-scale operation. The advantage of this latter method is that, if the design of the first set of blades is unsuitable, a new set can be made and tested in a fraction of the time taken to manufacture and test full-scale blades.

The various phases of development could be discussed in considerable detail, but this would involve another lecture equally long. Therefore, the details given here must suffice to indicate their direction and magnitude.

One of the most informative papers which has been given on the development of a specific engine was that by A. C. Lovesey, who described the development of the Rolls-Royce Merlin.* Those directly interested in the subject should read this valuable contribution to aviation engine art.

It is obviously important to have adequate test bed capacity for full-scale engines and, if a firm is building both piston engines and gas turbines, at least twelve and, perhaps, sixteen test beds will be required by the experimental department. These will differ in design and equipment, according to the type of engine tested and whether it is a

* *Aircraft Engineering*, July 1946.

piston engine, a propeller turbine or a jet turbine. At least four test beds will be required for each type of engine, plus four test hangars for engine-propeller tests.

This may appear to be a large number of test beds, but there must always be one available, at any time, for an engine which may be required to do a special test. And at least two test beds will be wanted for each engine type as its development progresses, for endurance tests.

I have frequently been asked what I consider should be the average number of engine-hours run per year in developing a prototype engine. Naturally, this will depend upon the type of engine and its complexity, particularly in the case of an entirely new engine of original design, where there are a large number of unknown factors. But, it should be possible to run 750-1,000 engine-hours in the first year and, as more models of the same prototype become available, the hours will increase rapidly in successive years. Depending upon the difficulties experienced during development, the engine will naturally be removed from the test bed many times for inspection and the redesign or modification of components and so on. Therefore, the total hours run in any one year will be represented by a number of tests of varying duration and by the number of experimental engines available.

The total running time, on the test bed and in flight before the first "Mark" of a prototype engine is ready for type test, will be 5,000 or 6,000 engine-hours in a period of three to three and a half years. It is difficult to be specific in quoting such figures, since there have been cases of engines needing 10,000 and even 20,000 engine-hours (five or six years) of experimental running before passing the type test. This was due to entirely original design bringing about quite unsuspected difficulties or, poor development.

The equipment required for calibrating and testing the components (compressor, combustion chamber and turbine wheel) of the gas turbine is far more elaborate and expensive than any used for the piston engine; although, in the particular case of the jet turbine, the test beds for testing the complete (full-scale) engine are somewhat less elaborate than those used for the piston engine.

In the past three or four years, equipment has been installed at some of the British and American firms which runs into hundreds of thousands of pounds sterling and tens of millions of dollars. Some of this equipment, when ordered, provided sufficient power to test components, such as the compressor, up to 12,000 h.p. But, even before the equipment was manufactured and installed, the power demands had risen to 20,000 h.p. on account of more advanced requirements for larger gas turbines.

In some cases the equipment was supplied at Government expense, but one or two firms provided comprehensive equipment at their own cost.

Air, in the quantity and condition required for testing gas turbines is an expensive commodity.

It is difficult to determine the practical limits of capital expenditure and size of plant for the individual manufacturer to possess, regardless of whether it is supplied at Government expense or by the firm. A capital outlay of £2,000,000 or £3,000,000 would be necessary to provide complete compressor and turbine testing equipment of sufficient power for propeller turbines of, say, 6,000-7,000 shaft horsepower and axial compressor jet turbines up to about 10,000 pounds static thrust. It is not practicable to consider equipment on this scale for any but the largest firms and, perhaps, not even for these.

If the existing sources of power are too small to test a complete component such as the compressor, the alternative is to test it at throttled conditions (reduced inlet pressure), or to remove some of the rows of blading in the compressor, thus reducing the power needed to drive it. By testing different blade rows, a close approximation can be made of its performance, although this is not so satisfactory as the former method, of throttling.

In my opinion, most engine manufacturers will have to improvise on the lines just described and it is the Government Research Establishments which must be supplied with all the elaborate equipment necessary for testing the components of large gas turbines. It has been suggested to me that if a satisfactory torquemeter were developed, fitting between the compressor and the turbine wheel, such a device would be an economical and efficient method of matching the compressor and turbine and so avoid the use, at the firms, of the more elaborate test equipment.

New equipment, apart from its cost and who is to pay for it, takes a long time to manufacture and deliver, in present world

conditions, particularly because the industrial firms who make it are engaged on other important contracts, quite outside the aviation field.

In order to test a complete and full-scale jet turbine at conditions of altitude and temperature simulating 11,000 metres (36,090 ft.) (tropopause) and minus 60° C., the cost of the test plant is equivalent to £20,000 for every pound of air per second capacity, provided for the engine. For instance, if an engine can consume, say, fifteen pounds of air per second at 11,000 metres, the total cost of the plant will be in the order of £20,000 × 15, or £300,000. Because of the great expense and time involved to build such a test tunnel it will be made sufficiently large, in the first place, to deal with the same amount of air at a still greater altitude, or a larger amount at the same altitude.

This brings me to the question of the relationship between Government Research Establishments and the aviation engine industry, since there is often uncertainty and, even, controversy in regard to their respective roles.

In Great Britain it was decided, after World War I, that the Royal Aircraft Factory (now the Royal Aircraft Establishment, or R.A.E.) should cease to design and manufacture full-scale engines in competition with the industry, which was then in being as a result of the war. Instead, its function would be to help the industry with scientific and technical advice; and also, by undertaking such research as would normally be beyond the scope or financial capacity of the industry.

This decision, in my opinion, was a right one, because an aviation engine industry composed of a wealthy participant (the Government) and the private firms, who in turn depend mainly upon Government support, could not escape the stigma of favouritism or nepotism, even if such accusations were ill-founded. In any case, the private firms usually have the greater incentive to energise their work and get things done more quickly than a Government Department which, because it is spending public funds, must be slower and more restrictive in procedure.

When considering the lack of financial support given to the R.A.E. by the Government, in the years between the two world wars, it is surprising that the staff were able to help the industry as much as in fact they did. But, during these lean years, the capacity of R.A.E. to run full-scale and altitude tests on the latest engines of the time was seriously restricted, although some useful flight testing of engines was done in the years between the two wars.

There were some at the R.A.E. who gave a great deal of time and thought to the shape of future engines and, as a result, in 1926, the axial type gas turbine was conceived. The credit for this and a good deal of work resulting from it goes to Dr. Griffith.

Then came Whittle, with the first practical aviation gas turbine of the jet propulsion type. His company, Power Jets Limited, had very meagre official support, both in the early days and, later, when his engine ran and proved itself a practical possibility. Eventually, in the recent war, Power Jets Limited, which earned Government support only in the form of contracts, was dissolved and the assets taken over by the Government, who reformed it into a Government controlled and capitalised company known as Power Jets (Research and Development) Limited. Later still, the actual research and testing facilities were taken from this company and formed into a Government Research organisation known as the National Gas Turbine Establishment, which exists to help all industry, aviation and otherwise.

The important question is: how can an Establishment of this kind help, and in what form should that help be given?

I think that the best and only practical way to help the aviation engine industry is for a Government to provide its Research Establishment with the more expensive and elaborate facilities such as the high altitude test tunnel and compressor and turbine test houses, with an available power of, say, 40,000 h.p. Aerodynamic test equipment for investigating blade forms and so on, must be provided and also, comprehensive facilities for combustion research. Some of this equipment already exists in the research Establishments and in the firms, both in Great Britain and America. America has the most complete research and testing facilities for gas turbines in the world.

The functions of such an Establishment would be to allow industry some use of the high altitude tunnel, and to design improved compressors and turbine wheels, with blading, which could be incorporated in specific engine designs if so desired; also to

provide data and advice on all combustion phenomena, and so forth.

Whatever the facilities provided for and by an Establishment, it is also necessary for the firms to have some (less elaborate) equipment, because they must be in the position to do tests at all times. The Establishment's equipment could not possibly cope with the demands of all the firms, and serious delays would be incurred if this were attempted.

An Establishment might wish to build an experimental engine but, inevitably, it would be a lengthy process compared with the similar efforts of industry and, even if it were of quite unorthodox and entirely original design, there would be little reason for doing this. Eventually the industry, with more experience of the mechanical design of such engines, would be asked to produce it and, in consequence, some redesign would be necessary in the light of their greater experience and particular production facilities. If the prototype were to be built by the Establishment most of the finished and semi-finished parts would have to come from outside sub-contractors, which is always a slow and costly procedure.

It must, therefore, be left to the aviation engine industry to produce new and advanced engines and, although the industry has sometimes been slow to appreciate something entirely new, it should be remembered that they cannot lightly discard the results of twenty or thirty years' experience, nor should they do so.

SUMMING UP.

The points of this lecture which I consider the most important are:—

1. If successful aviation engines are to be built, the industry must have properly controlled Government support in the form of sound technical requirements, followed by orders. The industry should not be nationalised, because of its highly competitive nature and the fact that, in times of peace, manufacturing licences and engines are sold to other countries, who may prefer to deal direct with the firm, or firms. These countries may also have a Government-supported aviation engine industry, which would resent competition with one that was Government-controlled, or nationalised.
2. New firms should not be encouraged if there is already a sufficient number of engine manufacturers to meet the military and civil airline demands, with some excess capacity to deal with foreign and overseas orders.

   If the industry is weak or ill-organised it is better to strengthen it and retain the technical personnel, rather than allow them to be scattered far and wide.
3. The minimum capacity of a firm should be based on the assumption that it can design and build one new high duty prototype engine of representative power in eighteen months or two years, and have it ready for production within five years. At the same time, it should be able to follow this with another new project and continue the forward development of one or two engine types which are already in production.

   To do this, the firm must be able to spend a large amount of money usefully and quickly.
4. Engines should always be built to meet specific aircraft requirements and therefore good liaison with the aircraft manufacturer and his designer is essential. There must be mutual trust and confidence in each other's products. But it is more important that the engine manufacturer enjoys the full confidence of the aircraft builder!
5. The successful engine manufacturer will not only possess comprehensive development facilities but he will also have an efficient engine installation and flight test department. He cannot afford to be without this because of the valuable information it gives him in regard to the behaviour of his engine at the various flight conditions, and the help he can give the aircraft manufacturer to make a good engine installation.
6. Very heavy expenditure is involved when providing complete development and testing facilities for gas turbine components; much heavier than that required for the equivalent facilities for the piston engine. Between £2,000,000 and £3,000,000 would be necessary to manufacture and install the equipment. Some firms prefer to be independent of the Government in regard to capital expenditure and provide their own, less elaborate, equipment. Others pay for the buildings (test houses) and also own

the land upon which these stand, but ask the Government to provide the experimental equipment within them, on the basis that this equipment may be rendered quickly obsolete.

7. More time is at present required (between ten per cent. and twenty per cent.) to design and manufacture a prototype propeller turbine of the axial compressor type, ready for test, than that required for a piston engine of equivalent power. Even a small propeller turbine with a two-stage centrifugal compressor exceeds, in total design hours, the time taken to design the more conventional piston engine of somewhat greater power. The most economical engine in terms of design and manufacturing hours is the classic Whittle type jet turbine, which absorbs about one quarter of the design hours of a large propeller turbine.

8. The life of a piston engine, as a type, has been about ten years and sometimes more, before becoming obsolete. During this time its performance will have been much improved by continuous development. This is important, since it takes five years to create an engine, from initial design to the start of production, and it would not be economical to design and develop an entirely new engine whenever an increase in performance was required. The Germans made this mistake in the recent war. Their development was indifferent and they seemed always to have in design and under test "bigger and better" engines.

   This also applies to the gas turbine, but it is unlikely that there will be the same large percentage increases in power which have been characteristic of the piston engine in the past twenty years. The gas turbine is virtually a "full throttle" engine and, therefore, the more that is learned of compressor, combustion and turbine behaviour, the greater the possibility of the prototype engine quickly giving its designed power in development, and the less likelihood of much increase during the life of the engine.

   If this eventually proves to be the case then a wider range of gas turbine types may always be necessary compared with the piston engine, which is very flexible in meeting the various aircraft requirements. In any case, the gas turbine is inherently less flexible than the piston engine in this respect and, if the engine manufacturer has to make a larger variety of types, the costs will increase considerably and the turbine may always be more expensive in consequence.

9. There should be little hesitation in cancelling the contract for an engine if there are sufficient reasons for so doing. The development of the engine is often allowed to continue, despite its lack of promise or altered, or cancelled, requirements. This is understandable, since a great deal of money may have been expended already on the engine's design and development. However, it is always better and more economical to cut the losses in such circumstances and discontinue the work. The difficulties in reaching a decision may also be political, where the Minister concerned will have to state the reasons for stopping the contract and for the apparent waste of money already spent. This is never an easy explanation to make to those who are ignorant of aviation engine technique. Therefore, I am firmly of the opinion that, in the first place, no such details of engine development should be given in any published Government Estimates, but that these Estimates should give an overall figure, for engine development, which allows for such contingencies.

10. There is no substitute for operating an engine in actual flight conditions and until the gas turbine, particularly the propeller turbine, has had many thousands of engine hours in the air, little will be known of its practical possibilities and running economy.

    The gas turbine has suffered more than any other engine from irresponsible publicity and changing requirements, largely because of the mistaken idea that it could be designed and developed quickly. The result is that gas turbines have been created on the drawing board and, as quickly, discarded for other creations, on paper. There has been already a recession and some aircraft which were to have propeller turbines are threatened with extinction or, at least, a reduction to the basis of one or two prototypes only. This is in

part caused by the vacillating policy, or lack of any policy, of those in control of civil aviation and also weakness on the part of the airline operators, mainly on the grounds of inadequate airport facilities for landing such aircraft, and the absence of proper flight control *en route*. But these deficiencies also apply, in a lesser degree, to present-day aircraft, with cruising speeds in the region of 300 Kms./hr. (186 m.p.h.) only, and are unlikely to be improved unless the pace is forced by those determined to operate advanced aircraft types.

CONCLUSION.

If this lecture is distinguished by any particular feature it is, perhaps, by the obvious lack of any mathematical formulae and other trifles of a similar nature. This omission has been deliberate because, in my opinion, there are many capable and experienced technicians who are fully conversant with the theoretical and technical aspects of the aviation engine, but there are few people who understand the art of making a successful engine. This, therefore, is my justification for presenting my experience in such a form. It is hoped that the lecture will be of some value to those who make aviation engines and to others who may have considered entering the same industry. A friend has suggested that the title of the lecture might have been "The Philosophy of the Aviation Engine." This exactly described my thoughts when writing it.

ACKNOWLEDGMENTS.

I wish to acknowledge the assistance given by Rolls-Royce Ltd. and to thank them for the valuable information and data they have generously made available to me.

Acknowledgments are due to the Electro-Motive Division of General Motors Corporation, for the information on their Diesel passenger locomotives and for permission to include it in the lecture; and to Sir William Stanier, who gave me the benefit of his long experience on steam locomotives.

It would have been quite impossible for me to have interpreted the subject matter of my lecture in the French language. The importance of any such interpretation is that it should represent exactly what the author has already attempted to convey in his own language.

Mr. Golovine, with his excellent knowledge and appreciation of the French language, together with his ability as an aviation engineer, has been able to translate faithfully my views. To him, I offer my most grateful thanks for this truly great effort and the large amount of time he has given so willingly.

I also wish to thank L. Armandias for his help and never failing courtesy, and H. Conway, R. Schlotel and S. D. Heron for their good advice.

I thank my firm, The Associated Ethyl Company Limited for giving permission to present the paper and my colleague, Mr. Goodacre, for his help and useful criticism.

Finally, I wish to say again how much I have appreciated the honour of being asked to present the first Louis Bleriot lecture.

At the conclusion of the Lecture a graceful vote of thanks was proposed by Monsieur Louis Breguet, a famous pioner of French aviation and constructor of many well-known and record-breaking aircraft.

M. Jarry then presented Air Commodore Banks with a medal depicting Bleriot's first crossing of the Channel. All the guests were later presented with similar medals which were designed for the occasion and were specially struck by the French Mint.

Later that evening a banquet in honour of the occasion was given by the President and Council of A.F.I.T.A. at the Aéro Club de France. Monsieur André Maroselli, Secretary of State for the French Armed Forces, presided.

Speeches were made by Monsieur Jarry, President of A.F.I.T.A., who welcomed the guests, especially Madame Louis Bleriot and her son, M. Jean Bleriot, and by Dr. Roxbee Cox, President of the Royal Aeronautical Society, Air Commodore Banks and Monsieur Maroselli. Dr. Roxbee Cox, again speaking in French, spoke of the friendship which had existed for many years between French and British aeronautical engineers and looked forward to still closer ties, with A.F.I.T.A. and the Royal Aeronautical Society going forward together. The Louis Bleriot Lectures would make great technical and scientific contributions to aeronautical knowledge and add to the friendship between France and Great Britain.

During his speech, Monsieur Maroselli announced in the name of the Government of the French Republic, the appointment of Air Commodore Banks as a Commandeur of the Légion d'Honneur for his services to France in connection with the development of aero-engines of all types. After the banquet and speeches, Monsieur Maroselli, in an impressive ceremony, invested Air Commodore Banks as Commandeur, Légion d'Honneur.

Among the guests present at the banquet were:—

Monsieur Allez, Vice-Président de l'Aéro Club de France; L. S. Armandias (representative in England of A.F.I.T.A.).

W. T. W. Ballantyne; Air Commodore F. R. Banks, F.R.Ae.S.; Monsieur Baril, de la Société des Ingénieurs Civils de France; Captain K. G. Bartlett, Royal Aero Club; E. L. Bass; Monsieur Benoit, Directeur Général Adjoint de l'O.N.E.R.A.; T. R. A. Bevan; Madame Louis Bleriot; Monsieur Jean Bleriot; Monsieur Louis Breguet, Membre d'Honneur d'A.F.I.T.A.

W. G. Carter, F.R.Ae.S.; Monsieur le Général Chassin de l'Etat Major de la Défense Nationale; Air Marshal Douglas Colyer, British Civil Air Attaché; Monsieur Matteo Connet, Directeur du Cabinet de Monsieur le Ministre de l'Air; H. G. Conway, F.R.Ae.S.; F. F. Crocombe, F.R.Ae.S.; Monsieur Cuny, Vice-Président de la Chambre Syndicale des Fabricants d'Accessoires.

Monsieur Marcel Dassault; Monsieur Desbrueres, Directeur Général d'Air France; R. N. Dorey, F.R.Ae.S.; Monsieur l'Inspecteur Général Dumanois, Membre d'Honneur d'A.F.I.T.A.

W. M. Evans.

L. G. Fairhurst; Monsieur le Colonel Fourquet, Directeur Adjoint au Cabinet de Monsieur le Ministre des Forces Armées.

Air Marshal R. A. George, representing the British Ambassador; Monsieur Gilles, Président Fondateur de l'A.F.I.T.A. et Président de la Fédération des Associations d'Ingénieurs; Monsieur Glasser; M. N. Golovine, A.F.R.Ae.S.; Monsieur le Général Guyot, Directeur Technique et Industriel.

Sir Frederick Handley Page, C.B.E., F.R.Ae.S., Past President R.Ae.S.; R. W. Harker; Monsieur l'Ingénieur Général Harlaut, Directeur de l'Ecole Nationale Supérieure de l'Aéronautique; A. S. Hartshorn, F.R.Ae.S., Scientific Liaison Officer at the British Embassy; Commander R. S. Hawkins, R.N., representing the British Naval Attaché; Monsieur Hereil, Président de la Chambre Syndicale des Industries Aéronautiques.

Thurstan James; Monsieur Jannes.

Monsieur l'Ingénieur Général du Génie Maritime Kahn, Directeur du Service des Constructions and Armes Navales.

Monsieur Lepicard; Monsieur le Commandant Lousteau, representing le Colonel Bezy de l'Etat Major des Forces Aériennes; Captain (E) M. Luby, R.N., F.R.Ae.S.; Flight Lieutenant P. G. Lucas, F.R.Ae.S.

Monsieur l'Amiral Nomy, Sous-Chef d'Etat Major Général de la Marine; Monsieur Norroy, Président de la Société des Ingénieurs de l'Automobile.

Monsieur Pissavy; Monsieur Henri Potez; Capt. J. L. Pritchard, Hon.F.R.Ae.S., Secretary R.Ae.S.

Group Capt. Silyn Roberts, F.R.Ae.S.; Monsieur l'Ingénieur Général Rouanet, Directeur du S.D.I.T.; N. E. Rowe, F.R.Ae.S., Vice-President R.Ae.S.; Dr. H. Roxbee Cox, F.R.Ae.S., President R.Ae.S.

Monsieur l'Ingénieur Général Sabine, Génie Maritime; H. Saxton; S. Scott Hall, F.R.Ae.S.; Wing Commander P. J. Stephenson, British Embassy; Major Oliver Stewart; Wing Commander R. H. Stocken, F.R.Ae.S.

Monsieur l'Ingénieur en Chef Thouvenot de la Direction de l'Aviation civile.

Colonel Valentyne, U.S.A. Military Air Attaché; Dr. Theodore von Karman.

THE ELEMENTS OF THE BUCKLING OF CURVED PLATES

by

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1. INTRODUCTION AND SUMMARY.

THE buckling of a round tube or curved plate under axial compression is an example of that class of instability in which the initial buckled form becomes itself at once unstable. As a result the buckle immediately develops to a large amplitude, often with loud noise. This class of instability has been aptly termed "oil canning" from a familiar example.

Thorough investigation of oil canning problems must always be tedious. As for any buckling problem it is essential to use large deflection theory and, since the amplitude of buckle rapidly becomes large, it is necessary also to consider in detail the distribution of the membrane (or mid-plane) stresses due to the buckle. This necessity, in combination with peculiar buckled forms, renders the complete solution even for a tube extremely difficult and tedious.[1, 2, 3, 4] Moreover, since the buckled form for a complete tube does not accord at all well with the edge conditions for a curved plate, the full analysis for the latter is almost prohibitively difficult.

In the present note this difficulty is largely evaded by "ignoring" the detail of the buckled form. By concentrating attention on the "wavelength" and amplitude of the buckle, the behaviour of the curved plate at and after buckling is represented qualitatively, and this representation is then rendered quantitative by reference to the limiting cases of tubes and flat plates, for which exact or nearly exact solutions are available. Finally, the quantitative representation is checked by comparison with experimental results.

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One important feature of the simplified analysis is that it permits consideration of the influence of initial irregularities from the true cylindrical form, and the results as finally presented include the effect of this factor. This elaboration of the basic theory is essential if the results are to provide a satisfactory guide to practical construction, because in these cases of what may be termed "unstable" buckling, the degree of initial irregularity has a most important influence on the behaviour of the structure; unless this influence be represented, comparison with experimental results must be completely stultified.

NOTATION

R = radius of curvature, measured to median plane of curved plate.
b = width of plate, measured circumferentially.
t = thickness of plate.
x = co-ordinate measured parallel to axis of tube or curved plate.
y = co-ordinate measured tangential to surface of tube or curved plate.
z = co-ordinate measured radially.
u, v = axial or circumferential displacement of a point in the median plane of the plate.
w = radial displacement of a point in the median plane of the plate, positive if outward.
λ = length typifying linear extent of buckle.
W = amplitude of wave, *i.e.*, maximum radial displacement of a point in the median plane of the plate from its original position.
W_o = initial amplitude of buckle in the form associated with length λ.
δ = maximum initial inward deviation of the plate surface from a straight edge of length b, placed anywhere on the plate along any generator.

$\theta = W/W_o$.

e_{xx} = strain in plate in x-direction, positive for extension.

e_{yy} = strain in y-direction, positive for extension.

e_{xy} = shear strain in x-y plane.

e_1 = applied axial strain, *i.e.*, relative axial movement of curved edges of plate under load, divided by plate length.

e_2 = applied circumferential strain, *i.e.*, relative circumferential movement of straight edges of plate under load, divided by plate width.

E = Young's modulus.

σ = Poisson's ratio.

$E' = E/(1-\sigma^2)$.

f_a = average axial stress in plate.

f_r = average circumferential stress in plate.

f_e = stress imposed on the plate along its straight edges, equals Ee_1 when the plate is free to expand circumferentially.

f_m = minimum post-buckling value of f_e.

f_c = nominal critical buckling stress.

$(1-\rho f_c)$ = minimum post-buckling value of f_a.

ψ, ξ, ζ = functions of x and y, representing forms of buckle, etc.

U = strain energy in plate.

U_d = strain energy of distortion of median plane of plate.

U_w = strain energy of warping of plate.

$A, B, C, L, M, N, F, K, L^1, M^1, N^1$ numerical constants.

2. BASIC FORMULÆ.

Taking axes Ox parallel to the axis of the tube or curved plate, Oy circumferentially and Oz radially, the stresses $\bar{zx}$, $\bar{yz}$ and $\bar{zz}$ are all zero at both surfaces of the sheet. It is presumed therefore that these stresses are negligible throughout the thickness of the sheet: that is, the sheet is regarded as "thin" and the problem is treated as one of plane stress. The strain energy U stored in a sheet under a system of plane stress, represented by extensions e_{xx} and e_{yy} and shear strain e_{xy} *is*

$$U = \tfrac{1}{4}E'\iint [(1+\sigma)(e_{xx}+e_{yy})^2 + (1-\sigma)\{(e_{xx}-e_{yy})^2 + e_{xy}^2\}]\,dxdydz \quad (1)$$

Where $E' = E/(1-\sigma^2)$, E is Young's modulus and σ is Poisson's ratio.

The displacements in the middle plane of the sheet are u axially, v circumferentially and w radially (outwards). Since we disregard shear strain through the plate thickness, the rotation of a line perpendicular to the sheet thickness may be identified with the rotation of the surface of the sheet itself: that is, this rotation is w_x* in the axial plane and $w_y + (v/R)$ in the radial plane, where R is the radius to which the plate is initially curved. The term v/R in the latter expression merely represents rotation about the centre of curvature of the sheet; this body rotation does not affect the bending stresses in the sheet and it may therefore be disregarded.

Then the displacements in the surface distant z from the middle surface of the sheet are $u + zw_x$ axially and $v + zw_y$ circumferentially, so that the tensile and shear strains are

$$\left.\begin{aligned} e_{xx} &= u_x + zw_{xx} + \tfrac{1}{2}w_x^2 \\ e_{yy} &= v_y + (w/R) + zw_{yy} + \tfrac{1}{2}w_y^2 \\ e_{xy} &= u_y + v_x + 2zw_{xy} + w_x w_y \end{aligned}\right\} \quad (2)$$

The last terms in the expressions represent the "membrane strains" due to the (large) deflection w; by the rotation w_x unit length axially becomes $(1+w_x^2)^{\frac{1}{2}}$ or approximately $1+\frac{1}{2}w_x^2$, so that the resultant strain is $\frac{1}{2}w_x^2$. Interaction between the displacements u and v on the one hand and the normal deflection w on the other, in respect of large values of w, is restricted to third order terms, which may be disregarded.

On substitution of the forms (2) in (1) and integration with respect to z, the cross products between terms with and without the factor z all disappear. Therefore the strain energy U divides into two parts, namely the strain energy of distortion of the mid surface of the sheet

$$\left.\begin{aligned} U_d = \tfrac{1}{4}E't\iint \{ &(1+\sigma)[u_x + v_y + (w/R) + \tfrac{1}{2}w_x^2 + \tfrac{1}{2}w_y^2]^2 \\ &+ (1-\sigma)[u_x - v_y - (w/R) + \tfrac{1}{2}w_x^2 - \tfrac{1}{2}w_y^2]^2 \\ &+ (1-\sigma)(u_y + v_x + w_x w_y)^2 \}\,dx\,dy \end{aligned}\right\} \quad (3)$$

and the strain energy of warping

$$\left.\begin{aligned} U_w &= \tfrac{1}{48}E't^3 \iint [(1+\sigma)(w_{xx}+w_{yy})^2 \\ &+ (1-\sigma)\{(w_{xx}-w_{yy})^2 + 4w_{xy}^2\}]\,dxdy \end{aligned}\right\}$$

or

$$\left.\begin{aligned} U_w &= \tfrac{1}{24}E't^3 \iint \{(w_{xx}+w_{yy})^2 \\ &+ 2(1-\sigma)(w_{xy}^2 - w_{xx}w_{yy})\}\,dxdy \end{aligned}\right\} \quad (4)$$

where t is the thickness of the plate.

It is shown in Appendix I that the second term in the integrand in (4) is zero for a rectangular plate of which the edges are held in the initial form, so that finally

$$U_w = \tfrac{1}{24}E't^3 \iint (w_{xx}+w_{yy})^2 dxdy \quad (5)$$

* Suffices are used to denote differentiation; thus w_x stands for $\delta w/\delta x$ and w_{xx} for $\delta^2 w/\delta x^2$ etc. This notation is much more concise than the more usual form.

3. STATEMENT OF PROBLEM.

The problem to be solved may now be stated as follows: Given the mean values of u_x, v_y and $u_y + v_x$, which determine the state of overall strain of the plate, it is required to define a function $W = \psi(x, y)$ with associated functions $u = W^2\xi(x, y)$* and $v = W^2\zeta(x, y)$ such that the sum of U_d and U_w as defined by formulæ (3) and (5) shall be a minimum. The functions ψ, ξ and ζ, all of which must conform to the boundary conditions imposed on the edges of the plate, should strictly be determined uniquely by this minimal condition. However, in practice, complete analysis to this end, difficult enough in the case of a flat plate [5], is virtually impossible for a curved plate. The best that can be done is to choose as appropriate a form for ψ as possible and to derive the corresponding terms for ξ and ζ. Even this procedure has not been followed for the curved plate of rectangular form; but the method is illustrated for the case of the complete tube in ref. 2.

In that reference it will be seen that one most important feature of the process of buckling is modification of the form of ψ as the buckle develops. This modification, controlled as it must be by considerations of least energy, is extremely difficult to represent analytically. An analogous instance is discussed in ref. 5, §14, and this example illustrates the considerations which govern such changes of buckled form.

The associated functions ξ and ζ have been written above with amplitudes proportional to W^2. This is entirely appropriate to flat plates (cf. ref. 5, §10), but in the case of curved plates there may also be associated u and v functions with amplitudes proportional to W; this possibility is related to the effect of initial irregularities and it is discussed further in §11 below.

* In order to preserve correct dimensions, while maintaining the functions ξ and ζ non-dimensional, these functions should strictly be defined by terms such as $u = (W^2/t)\,\xi(x, y)$ etc.; but this refinement is unnecessary here.

4. "IGNORING" THE BUCKLED FORM.

The difficulties briefly reviewed above are so forbidding that some means must be found to evade them; not principally because detailed analysis would involve excessive labour, but rather because the main thread of the argument and the conclusions would be too heavily obscured by the complexity of the analysis. This evasion is effected by "ignoring" the wave form as explained in the next paragraph.

If we knew the form of ψ and of the associated functions ξ and ζ, the process of evaluation of U_d and U_w from formulæ (3) and (5) would reduce merely to the computation of certain definite integrals; so that for instance we should have $U_w = CW^2$, where C would be a constant, of which the value would be determined by the dimensions of the plate and the form of ψ. The process of "ignoring" ψ is to re-write formulæ (3) and (5) in this and similar forms, while leaving the values of the coefficients such as C to be determined by other means.

At the same time one essential elaboration of this procedure is to represent the effect of differentiation of $W\psi(x, y)$ with respect to either x or y by division of W by an unknown "wavelength" λ: that is, we write $\iint w_x^2\,dxdy = A(W/\lambda)^2$ and $\iint w_y^2 dxdy = B(W/\lambda)^2$. Since the coefficients A and B are treated as unknowns, this elaboration is in itself unobjectionable and, since the ratio of A to B is uncontrolled, the use of the same λ for both differentiations is also permissible. Later, when the coefficients A and B will be treated as virtual constants and λ alone will be varied, we shall, in effect, be assuming that the wave shape is independent of its size (wavelength), and that the strain energies do in fact vary with the wavelength in the manner represented by these forms. These implicit assumptions are certainly not justified over wide variations of buckled form, but over moderate ranges of variation they should afford a reasonable approximation.

5. QUALITATIVE ANALYSIS OF THE CONDITIONS FOR EQUILIBRIUM.

On the basis described in §4, for a plate subjected to axial compressive strain e_1 and to circumferential compressive strain e_2, we may write, using formulæ (3) and (5),

$$U_d = \tfrac{1}{2}E't\,[e_1^2 + e_2^2 + 2\sigma e_1 e_2 - (e + \sigma e_2)\,A\,(W/\lambda)^2 - (e_2 + \sigma e_1)\,\{B\,(W/\lambda)^2 + 2C\,(W/R)\} + L'\,(W/R)^2 + \tfrac{4}{3}M'\,(W^3/R\lambda^2) + \tfrac{1}{2}N'\,(W/\lambda)^4] \quad (6)$$

and

$$U_w = \tfrac{1}{2}E't^3F\,(W/\lambda^2)^2 \quad . \quad . \quad . \quad . \quad (7)$$

The coefficients A, B, C, L', M', N' and F all being unknown, the numerical coefficients associated with them have been chosen merely in anticipation of simplification later.

By differentiation with respect to e_1 and e_2 in turn, the average stresses, f_a axially and f_r circumferentially, are

$$f_a = E'[e_1 + \sigma e_2 - \tfrac{1}{2}A(W/\lambda)^2 - (\sigma/2)\{B(W/\lambda)^2 + 2C(W/R)\}] \quad . \quad . \quad (8)$$

and

$$f_r = E'[e_2 + \sigma e_1 - (\sigma/2)A(W/\lambda)^2 - \tfrac{1}{2}\{B(W/\lambda)^2 + 2C(W/R)\}] \quad . \quad . \quad (9)$$

In the absence of normal pressure on the plate, differentiation with respect to W gives

$$\left.\begin{aligned} &-(e_1+\sigma e_2)\,A(W/\lambda) - (e_2+\sigma e_1)\{B(W/\lambda) + C(\lambda/R)\} \\ &+ L'(\lambda/R)^2(W/\lambda) + 2M'(\lambda/R)(W/\lambda)^2 + N'(W/\lambda)^3 + F(t/R)^2(R/\lambda)^2(W/\lambda)^2 = 0 \end{aligned}\right\} \quad (10)$$

If the circumferential stress f_r is zero (as we shall assume), by substitution in formula (10) for e_2 from formula (9), either $W=0$ or

$$-(1-\sigma^2)e_1A + L(\lambda/R)^2 + 2M(\lambda/R)(W/\lambda) + N(W/\lambda)^2 + F(t/R)^2(R/\lambda)^2 = 0 \quad (11)$$

where $L = L' - C^2$, $M = M' - \frac{3}{4}C(B+\sigma A)$ and $N = N' - \frac{1}{2}(B+\sigma A)^2$. Moreover, by substitution for e_2 from formula (9) with $f_r = 0$ in formula (8)

$$f_a = E\{e_1 - \tfrac{1}{2}A(W/\lambda)^2\} \quad . \quad . \quad . \quad . \quad (12)$$

By suitable definition of unit amplitude of ψ in the form of $w = W\psi(x, y)$ it is possible and convenient to make $A = 1/(1-\sigma^2)$, when formula (12) may be written in the form

$$f_e - f_a = \tfrac{1}{2}E'(W/\lambda)^2 \quad . \quad . \quad . \quad . \quad (13)$$

where $f_e\,(=Ee_1)$ is the stress imposed on the plate along its edges, which are held straight. Similarly formula (11) may be written in either of the alternative forms

$$f_e - f_c = E'\{N(W/\lambda) + 2M(\lambda/R)\}(W/\lambda) \quad . \quad . \quad . \quad . \quad (14)$$

where

$$f_c = E'\{L(\lambda/R)^2 + F(t/R)^2(R/\lambda)^2\} \quad . \quad . \quad . \quad . \quad (15)$$

or

$$f_e - f_m = (E'/N)\{N(W/\lambda) + M(\lambda/R)\}^2 \quad . \quad . \quad . \quad . \quad (16)$$

where

$$f_m = f_c - (E'M^2/N)(\lambda/R)^2 \quad . \quad . \quad . \quad . \quad (17)$$

6. CHARACTERISTICS OF BUCKLING.

The relation between the edge stress f_e and the buckle amplitude W defined by formula (14) or (16) is shown in Fig. 1; it is simply a parabola with its axis parallel to the axis of f_e but displaced to the side corresponding to negative values of W through a distance proportional to (λ/R). For a perfectly cylindrical plate no buckle can be formed until $f_e > f_c$, but as soon as that critical stress is reached inward buckling (W negative) results in a *reduction* of f_e, and therefore the buckle develops immediately to a large amplitude. This effect is the more marked the greater the offset of the axis of the parabola from the axis of f_e, that is, at high values of (λ/R).

The greatest possible value of (λ/R) is that for a complete tube, for in that case the value of λ is unrestrained by the edge conditions, and we are free to choose that value which makes the value of f_e defined by formula (15) a minimum. This minimum value is $2E'(FL)^{\frac{1}{2}}(t/R)$ and occurs when $(\lambda/R)^2 = (F/L)^{\frac{1}{2}}(t/R)$. Thus the fall of load at buckling is most marked in these strongly curved plates and tubes, for which the buckling stress is high.

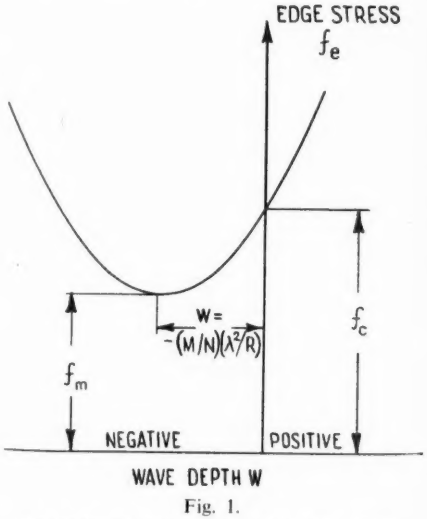

Fig. 1.
Variation of wave depth with edge stress.

At the other extreme for the flat plate the parabola is symmetrical about the axis of f_e, buckling in either sense is equally probable and f_e continuously increases with W.

By elimination of (W/λ) between formulæ (13) and (14) it can be shown that the relation between f_e and f_a after buckling is also a parabola (Fig. 2). This parabola touches the

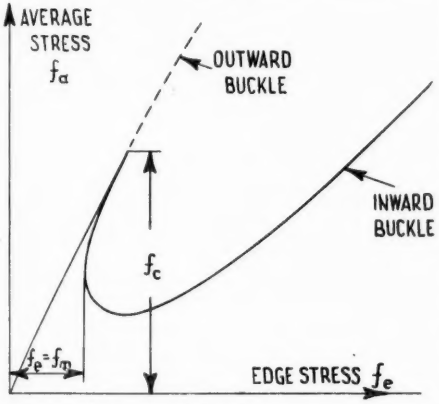

Fig. 2.
Variation of average stress with edge stress.

elastic line $f_a=f_e$ at the value f_e and has a vertical tangent (minimum value of f_e) at $f_e=f_m$. The lower (regressive) branch of this parabola corresponds to negative values of W and the upper branch to positive values. If negative values of W could be avoided, the curved plate or tube after buckling would behave much like a flat plate—indeed slightly better; but in practice inward buckling is difficult to prevent (see §11 below).

If inward buckling does occur the least value of f_a after buckling is given by

$$f_c - f_a = E' \{ 2M^2/(2N-1) \} (\lambda/R)^2 \qquad (18)$$

Thus the fall of load after buckling is also proportional to $(\lambda/R)^2$, which for a complete tube or wide plate is itself proportional to (t/R); whereas for a narrow plate the fall is less because the value of λ is restricted.

7. LIMITATIONS OF THE PARABOLIC FORMULÆ.

Qualitatively formulæ (13) to (15) and Figs. 1 and 2 represent all the essential characteristics of the buckling of curved plates under axial compression (see, for instance, ref. 3); but in attempting to render this representation also quantitative, certain limitations of these formulæ must be appreciated.

If the wave form of the buckle were completely specified, the parameters F, L, M and N would be known numerical coefficients and the definition of λ could be made precise, therefore, so long as the *wave form* of buckle remains unchanged, the description above of the behaviour after buckling is exact and the relation between f_e and f_a is indeed parabolic.* Now actually the wave form varies from plate to plate according to the value of b^2/Rt, where b is the circumferential width of the plate; for a flat plate the buckled form consists of "squares"[5]; for a complete tube it consists of "diamonds"[2]; and for a curved plate the gradual transition from squares to diamonds as the value of b^2/Rt is increased, as illustrated in ref. 6.

Moreover, even for each particular plate the wave form does not remain unchanged during the whole process of buckling; as the depth of buckle increases the wave form may be "modified" or it may be "changed." "Modification" consists in a gradual alteration of the type described in ref. 5; "change" is the sudden alteration of the type described in ref. 2. In the case of the curved plate modification is virtually impossible and the changes of wave form, governed as they are by considerations of least energy, are extremely difficult to compute. [2] [5, §17]

The process of change of wave form cannot be represented by formulæ (13) to (17). Although these formulæ with appropriate values of the unknown parameters must represent both the old and the new wave forms, the transition from old to new is not necessarily possible at the first point of intersection of the corresponding $f_a - f_e$ curves (Fig. 3). The actual transition may be considerably delayed, or it may even be entirely prevented; but formulæ (13) to (17) afford no clue at all as to its occurrence.

For this reason we can expect to assign values to the parameters in formulæ (13) to (17) to represent only a limited portion of the $f_a - f_e$ curve, over which the wave form is to be presumed unaltered. In respect of flat or only slightly curved plates this representation will certainly suffice; but for a wide curved plate or a complete tube a wave form appropriate to the initiation of buckling is unlikely to be appropriate at the large buckle

* This is equally true for a flat plate, but in that case the parabola is infinitely narrow and degenerates into a straight line (cf. ref. 5 §9).

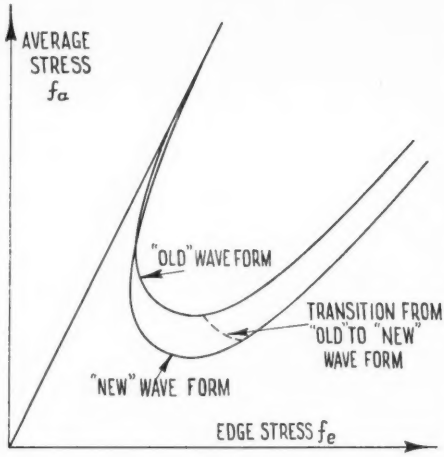

Fig. 3.
Change of buckled wave form.

amplitude, which because of the fall of load at buckling will be reached immediately after the first buckle. Thus the requirement of constant wave form is in this case virtually impossible to fulfil.

Completely to evade this difficulty is impossible and any representation of the behaviour of a wide plate or complete tube by adoption of a single set of values of the parameters in formulæ (13) to (17) is necessarily a compromise; yet for practical purposes it does prove feasible to adopt a single curve. This is explained below, where the method of representing the variation of behaviour according to the value of b^2/Rt is also explained.

8. INITIAL BUCKLING.

In the absence of initial irregularities (of which the effect is discussed in §10 below) before buckling begins $W=0$. Then by formula (14) transition from the unbuckled to the buckled state is impossible until $f_e > f_c$. Thus f_c is the critical stress for initial buckling of a perfectly cylindrical plate or tube. Formula (15) may be written in the form

$$f_c = E' \{ L (\lambda/b)^2 (b^2/Rt) + F (b/\lambda)^2 (Rt/b^2) \} (t/R) \quad . \quad (19)$$

If the value of λ is quite unrestricted, the least value of f_c is

$$2E' (FL)^{\frac{1}{2}} (t/R) \quad . \quad . \quad (20)$$

Clearly this value is that appropriate to a long complete tube, in which there is no external constraint on the buckled form, so that the value of the coefficient $(FL)^{\frac{1}{2}}$ may be assigned by comparison with the known formula for this case.

$$f_c = 0.6E (t/R) \text{ (ref. 2)} \quad . \quad . \quad (21)$$

The corresponding value λ_o of λ is defined by the relation

$$(\lambda_o^2/Rt) = (F/L)^{\frac{1}{2}} \quad . \quad . \quad (22)$$

In a curved plate the limited width b may be insufficient to accommodate the wave form corresponding to this value λ_o of λ, so that a smaller value may be forced. In the limit for a flat plate, when $R \to \infty$, formula (19) reduces to

$$f_c = E'F (b/\lambda)^2 (t/b)^2 \quad . \quad . \quad (23)$$

and we may identify the coefficient $F (b/\lambda)^2$ with the known (numerical) value corresponding to the edge conditions specified (ref. 5, Tables 1 and 2). Moreover, without loss of generality we may assume that for the flat plate $\lambda = b$.

Finally, in order to provide for smooth transition from the case of the flat plate to that of the complete tube it is necessary to assume some mode of variation of (λ/b) with (b^2/Rt), which shall conform to the limiting conditions $(\lambda/b)=1$ when $b^2/Rt=0$ and $(\lambda^2/Rt)=$const. when b^2/Rt is large. Owing to the form of formula (19) the values of f_c are affected only very slightly by the mode of variation of λ/b between these limits, and the formula

$$(b/\lambda)^4 = 1 + (b^2/Rt)^2/K \quad . \quad (24)$$

where K is a numerical constant, proves satisfactory.

For plates with clamped edges, the formula (19) then becomes

$$\{ f_c/E (t/b)^2 \} = 6.31 (b/\lambda)^2 + 0.01425 (\lambda/b)^2 (b^2/Rt)^2 \quad . \quad (25)$$

with the value of b/λ defined by formula (24). The value assumed for K determines the lowest value of b^2/Rt at which the full tube buckle occurs. According to ref. 2, by reference to the number of waves circumferentially, this should occur at about $b^2/Rt=200$, corresponding to $K=447$; but experimental evidence suggests that all the essential characteristics of the buckling of a complete tube are reproduced in much narrower plates. Therefore the value $K=475$ corresponding to the limiting value $b^2/Rt=78$ has been adopted. In any case such slight variation of the value of K does not otherwise appreciably affect the representation.

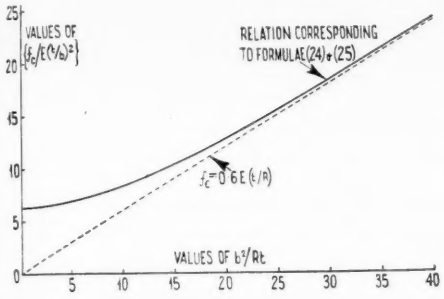

Fig. 4.

Variation of initial buckling stress with the value of b^2/Rt.

The relation (25) is shown plotted in Fig. 4, for comparison with the curve computed in ref. 7. The values of f_c computed from formula (25) lie wholly below this curve; but this curve is certainly too high because the wave forms on which the computations were based are only approximations to the true forms.

9. BEHAVIOUR AFTER BUCKLING.

In order to represent the behaviour of curved plates after buckling we choose for each value of b^2/Rt a single parabola as defined by formulæ (13) to (15) with the value of f_c represented in §8 and with appropriate values of f_a and of df_a/df_e at $f_e = 2f_c$. For a flat plate with clamped edges appropriate values are

$f_a = 1.5f_c$ and $df_a/df_e = 0.5$ at $f_e = 2f_c$ (ref. 5)

and for a complete tube

$f_a = 0.625f_c$ and $df_a/df_e = 0.25$ at $f_e = 2f_c$ (ref. 2).

These data determine the values of the parameters M and N in formula (14) for the cases $b^2/Rt = 0$ and $b^2/Rt = 78$.

By elimination of W/λ between formula (13) and (14), we obtain the relation

$$\{ f_c + (2N-1) f_e - 2Nf_a \}^2 = 8M^2E' (\lambda/R)^2 (f_e - f_a) \quad . \quad (26)$$

Then denoting the fall of load at buckling by ρf_c, so that ρ is the proportionate fall, from formula (18), we have

$$\rho f_c = E' \{ 2M^2/(2N-1) \} (\lambda/R)^2 \quad . \quad (27)$$

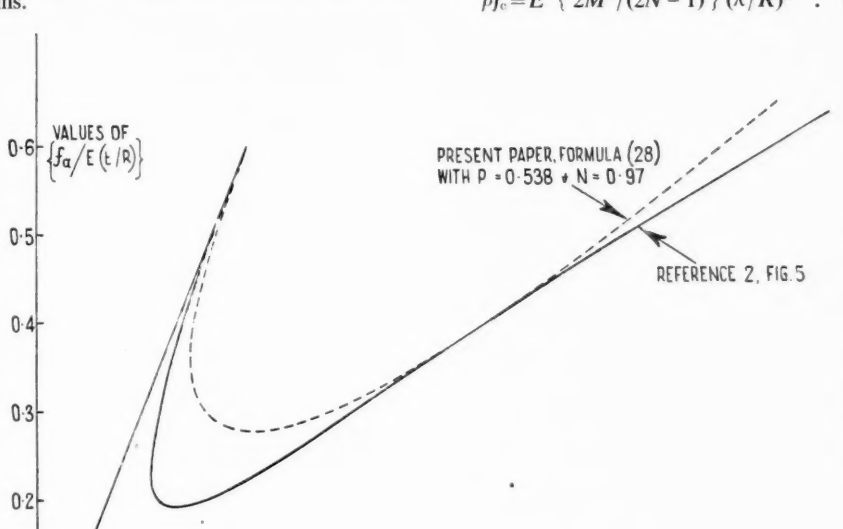

Fig. 5.

Comparison between exact and approximate stress-strain curves for the complete tube.

Using this formula to eliminate M from formula (26), this latter formula becomes

$$\{(2N-1)f_e - 2Nf_a + f_e\}^2 = 4\rho(2N-1)f_e(f_e - f_a) \quad . \quad (28)$$

For the flate plate $N=1$ and $\rho=0$; for the complete tube also N differs very little from unity, but ρ=about 0.523. The theoretical value of ρ (ref. 2) is about 0.68; the lower value here adopted is occasioned by the need to fit a *single* parabola as explained in §7. That the true "trough" of the $f_a - f_e$ curve is thus bridged should not matter at all in practice, because in any ordinary structure f_e must continuously increase and the trough will be jumped [6]. The comparison between the exact and the present approximate $f_a - f_e$ curves for the complete tube is shown in Fig. 5.

In order to represent the behaviour of plates with intermediate values of b^2/Rt, it would be reasonable to assume that $N=1$ throughout and to adopt a series of values of ρ graded between 0 and 0.523. However, the slope df_a/df_e at $f_e=2f_e$ is

$$\frac{2N-1}{2N}\left[1 - \frac{1}{2N-1}\left\{\frac{\rho(2N-1)}{2N(\rho+1)-1}\right\}^{\frac{1}{2}}\right] \quad (29)$$

and with $N=1$ throughout this slope is reduced too rapidly below the value $\frac{1}{2}$ at low values of ρ.

At this stage appeal to experimental results becomes advisable and from these results[6], it appears that at low values of b^2/Rt the effect of curvature is almost negligible so that such plates behave almost exactly as flat ones. For this reason, for the case $b^2/Rt=10$ at $f_e=2f_e$ we take $df_a/df_e=\frac{1}{2}$ and $f_a=1.384$, the

TABLE I.

Coefficients defining $f_a - f_e$ curves.

b^2/Rt	0	10	20	30	40	50	60	70	78
b/λ	1.00	1.05	1.16	1.30	1.44	1.58	1.71	1.83	1.93
N	1.00	1.18	1.15	1.12	1.09	1.06	1.03	1.00	0.982
ρ	0	0.060	0.159	0.237	0.304	0.362	0.416	0.467	0.523
$f_e' = \{f_e/E(t/b)^2\}$	6.31	8.24.	12.77	18.27	24.10	30.03	36.00	42.00	46.80

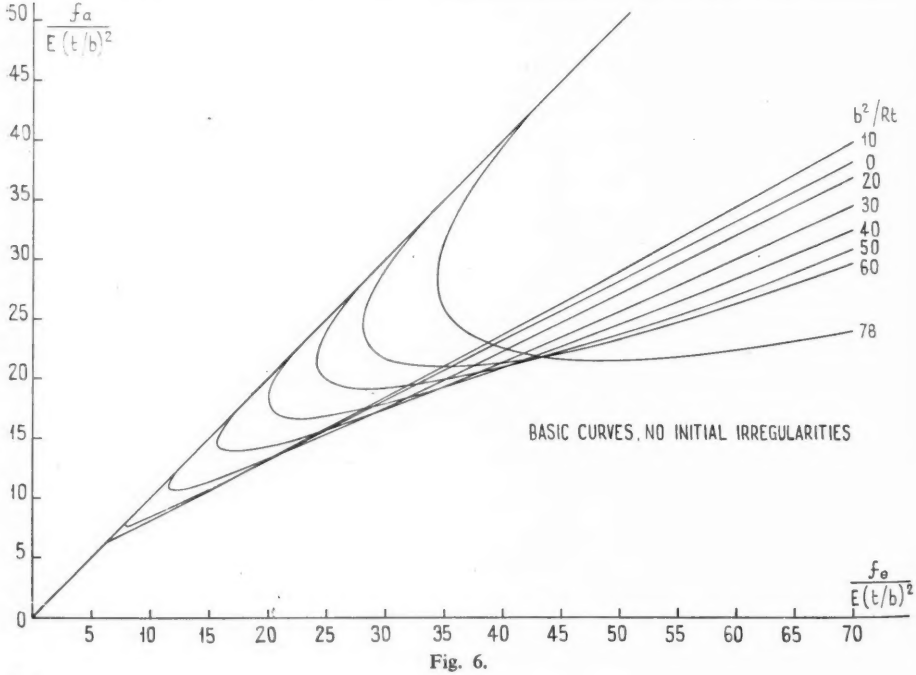

Fig. 6.

latter value being determined by the condition that the tangent to the $f_a - f_e$ curve at $f_e = 2f_c$ should pass through the line $f_a = f_e$ at the value $6.31E(t/b)^2$ representing the initial buckle of the flat plate. These assumptions lead to the values $N = 1.18$ and $\rho = 0.06$.

With these limit values and again by reference to experimental results, the values of ρ and N adopted are given in Table I.

The corresponding family of $f_a - f_e$ curves are shown in Fig. 6.

10. THE EFFECT OF INITIAL IRREGULARITIES.

The curves shown in Fig. 6 are still of little use for comparison with experimental results, because the effect of initial irregularities is not represented. In respect of initial buckling stress particularly, this factor has a dominant influence in suppressing the sharp cusp shown in these curves.

In order to represent the effect of initial irregularities in the plate the buckled form may be re-specified by the expression $w = (W + W_o)\psi(x, y)$, where W_o is the initial amplitude in the mode ψ and W is now the increment of amplitude resulting from buckling. By this change formula (7) for U_w remains unaltered, but formula (6) for U_d now has $\{ W(W + 2W_o)/\lambda \}^2$ for $(W/\lambda)^2$ wherever the latter form appears. Then formula (13) becomes

$$f_e - f_a = \tfrac{1}{2}E'W(W + 2W_o)/\lambda^2 \quad . \quad (30)$$

while formula (11) reduces to

$$-(1-\sigma^2)e_1 A \{ (W + W_o)/W \} + L(\lambda/R)^2 + 2M''(\lambda/R)\{ (W + \tfrac{4}{3}W_o)/\lambda \} + N\{ (W + W_o)(W + 2W_o)/\lambda^2 \} + F(t/R)^2(R/\lambda)^2 = 0 \quad (31)$$

Where

$$M'' = M - \tfrac{1}{2}C(B + \sigma A)\{ W_o/(W + \tfrac{4}{3}W_o) \}$$

Since C is small, the difference between M'' and M is slight even when $W = 0$, and this difference rapidly decreases as W increases. Accordingly this difference may safely be ignored, when the values of all the coefficients A, L, M, N and F remain as previously defined.

The formulæ (30) and (31) may be written

$$f_e - f_a = \tfrac{1}{2}E'(W_o/\lambda)^2\theta(\theta + 2) \quad . \quad (32)$$

and

$$f_e = \{ \theta/(\theta + 1) \} [f_c + E'(W_o/\lambda)\{ 2M(\lambda/R)(\theta + \tfrac{4}{3}) + N(W_o/\lambda)(\theta + 1)(\theta + 2) \}] \quad . \quad (33)$$

Where $\theta = W/W_o$ represents the ratio in which the initial irregularity is enlarged, and f_c is the nominal critical stress as defined by formula (15) or (25). By dividing both sides of formulæ (32) and (33) by $E(t/b)^2$ and using formula (27), these relations may be put in the form

$$f_e' - f_a' = \tfrac{1}{2}\alpha^2\theta(\theta + 2) \quad . \quad . \quad (34)$$

and

$$f_e' = \{ \theta/(\theta + 1) \} [f_c' + \alpha \{ 2(2N - 1)\rho f_c' \}^{\frac{1}{2}} (\theta + \tfrac{4}{3})] + N\alpha^2\theta(\theta + 2). \quad . \quad (35)$$

where

$$f_e' = \{ f_e/E(t/b)^2 \} \quad \text{etc.}$$

and

$$\alpha = (W_o/t)(b/\lambda)/(1 - \sigma^2)^{\frac{1}{2}}.$$

With the values of f_c', ρ and N given in Table I, by assuming a series of values of θ from zero upwards the relation between f_a and f_e may be plotted for any assumed value of α. Taking into account the factor $(b/\lambda)/(1 - \sigma^2)^{\frac{1}{2}}$ these values of α correspond to assumed values of W_o/t.

11. ORIGIN AND NATURE OF THE INITIAL IRREGULARITIES.

If the value of (W_o/t) in formulæ (34) and (35) is assumed positive the curve of f_a against f_e does not turn back on itself but proceeds ever upwards and tends asymptotically to the upper branch of the parabola in Fig. 2. On the other hand, if a negative value of W_o/t be assumed, the curve reaches a maximum value below f_c and proceeds downwards and backwards to follow the lower branch of the parabola, to which again it tends asymptotically.

Now the buckled form of a curved plate or tube is not unique; even when the form is definite its position (or phase) in the plate may be subject to variation. Therefore in seeking to avoid negative values of W_o in one form, there is in practice a grave liability to introduce negative amplitudes in another. For this reason complete avoidance of negative amplitudes would appear hopeless; nevertheless there is some experimental evidence that the desired end can be achieved.[8].

In order to estimate the appropriate value of W_o to represent the state of any actual plate, appeal must be made to general experience based on comparison with the limited number of tests which have been made in sufficient detail.[6] This point is discussed further in Appendix II.

In addition to the initial irregularities present in the plate before it is loaded at all, consideration must also be given to the possibility of irregularities being introduced during the loading prior to the attainment of the maximum load. In deriving formula (6)

from formula (3) this possibility was glossed over, although it was mentioned at the end of §3 in the reference to the possible need to introduce u and v functions proportional to the wave depth W in addition to those functions proportional to W^2.

When a tube is loaded axially it expands laterally, so that if $u_x = -e$, $v_y + w/R = \sigma e$. If the tube is long so that radial constraint may be ignored, it is reasonable to assume $w = R\sigma e$ and $v_y = 0$. On the other hand a narrow plate may not be free to expand thus radially, and even a complete tube may be restrained by stringers and frames. In the case of a plate having all its edges held in the original cylindrical form, $w = 0$ at these boundaries. In the central part of the plate remote from its edges w may tend to the value $R\sigma e$ and the complete formula for w must take some form like

$$w = R\sigma e \sin(\pi x/a) \sin(\pi y/b),$$

where a is the length of the plate and b is its circumferential width. Then for least energy associated u and v functions also proportional to σe are needed, because otherwise the condition $v_y + w/R = \sigma e$ cannot be fulfilled. In effect, by proceeding from formula (3) above to formula (6) the plate has been assumed to be free to expand laterally and the deflection w has been computed from its expanded form just prior to buckling.

This effect of restraint at the plate edges in causing departure from the true cylindrical form before actual buckling occurs might be considered the last straw which renders a difficult problem completely intractable. Even the outline analysis described above would become hopelessly complicated were this effect represented. However, it is improbable that the effect appreciably modifies the behaviour of the plate otherwise than by affecting the distribution and amplitude of those departures from the true cylindrical form, which constitute initial irregularity. Here it is merely concluded that restraint at the plate edges renders the "perfectly cylindrical plate" a meaningless abstraction, and that all plates, however perfectly made, must be treated as having a finite amplitude of initial irregularity.

APPENDIX I.

Proof that for a rectangular plate $\iint (w_{xx}w_{yy} - w_{xy}^2)\,dx\,dy$ is zero.

$$\iint w_{xx}w_{yy}\,dx\,dy = \int [w_x w_{yy}' - \int w_x w_{xyy}\,dx]\,dy,$$

by integration by parts

$$= -\iint w_x w_{xyy}\,dx\,dy,$$

because w_y and therefore w_{yy} also is zero at both limits of x,

$$= -\int [w_x w_{xy} - \int w_{xy}^2\,dy]\,dx,$$

again by integration by parts,

$$= \iint w_{xy}^2\,dx\,dy,$$

because w_x is zero at both limits of y.

It should be noted that this proof, depending as it does on $w_y = 0$ at both limits of x and $w_x = 0$ at both limits of y, is restricted to rectangular plates with their edges held in a plane. For other shapes of plate in general $\iint (w_{xx}w_{yy} - w_{xy}^2)\,dx\,dy$ is not equal to zero.

APPENDIX II.

Comparison of theoretical with experimental results.

A substantial number of results of tests on curved plates in compression have been published. [6, 8, 15, 17, 19, 22, 23, 24, 25, 26, 30, 31, 37, 38, 43]. For the purpose of checking the predictions of the theory developed above, it is essential that the tests should be systematic, that is that they shall have been conducted under constant edge conditions, with variation of the curvature parameter b^2/Rt only. Moreover, in view of the marked effect of initial irregularities it is most desirable that the initial shape of the plates shall have been accurately determined. Of the tests available to us, the only series that complied with these requirements was that of ref. 6, published by the National Research Council of Canada. These tests, therefore, have been used to check that the assumptions which have been introduced in the theory are adequate, while other results have been scrutinised only to make sure that they do not conflict with the conclusions drawn.

Because of the several assumptions in the theory, in particular that of constant wavelength and buckle shape after buckling, the shape of the load-deflection diagram of any individual plate cannot be expected to agree everywhere closely with that indicated by the theory. In addition, in the tests part of the post-buckling curve is "jumped"; the extent of this jump depends as much on the characteristics of the testing machine as on those of the plate. Comparison of individual load-deflection diagrams with corresponding theoretical curves is therefore of little value; in spite of this, it is thought that the following analysis allows a number of useful conclusions to be drawn.

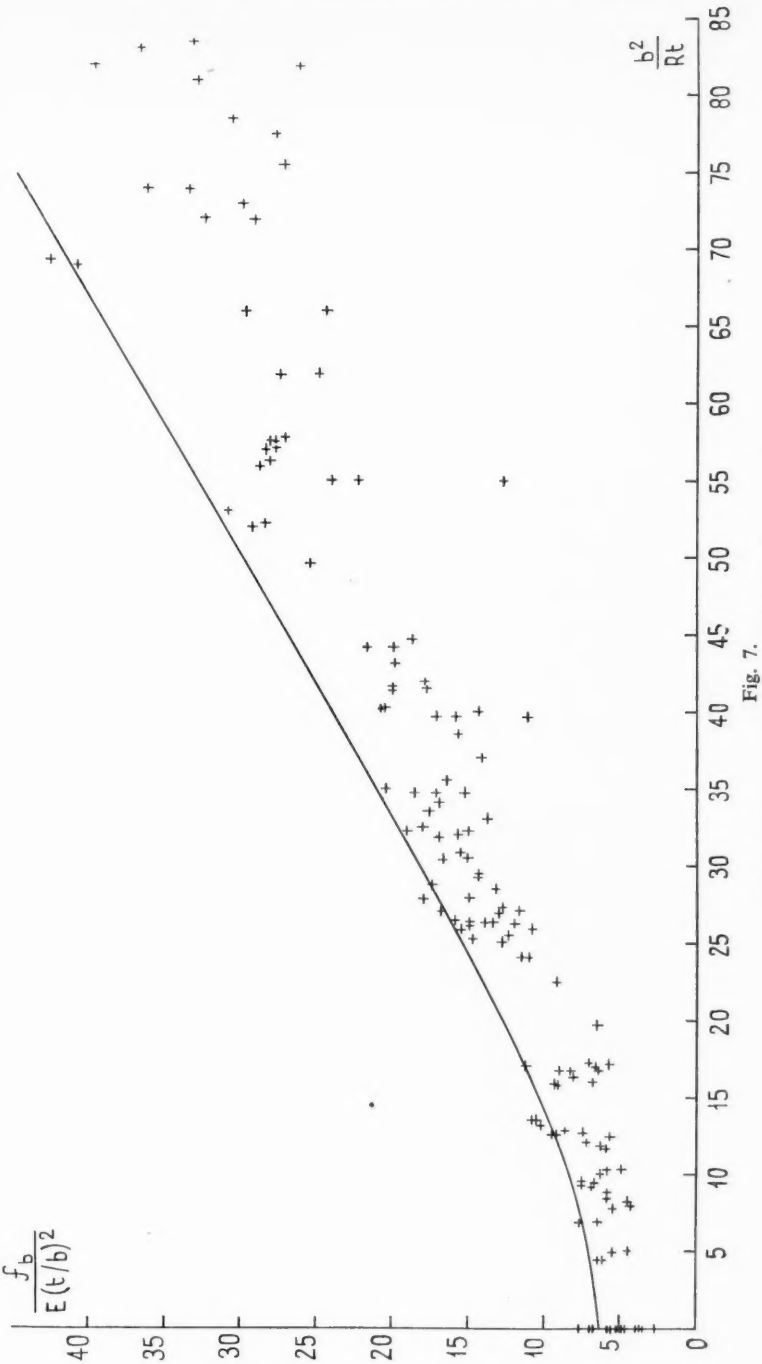

Fig. 7.
First buckling stresses of curved plates from ref. 6.

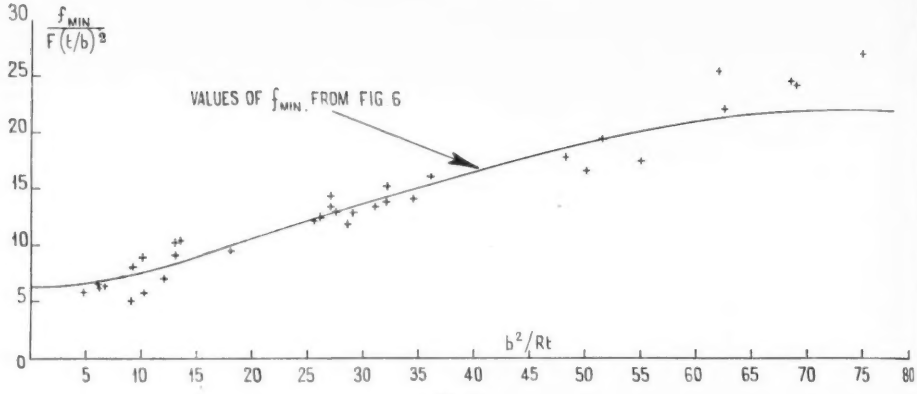

Fig. 8.
Minimum post-buckling stresses of curved plates.

BUCKLING STRESS AND FALL AT BUCKLING.

One striking feature of the theoretical curves is the marked effect of initial irregularities on the maximum stress at buckling, in contrast to the insensibility of the average stress in the plate after buckling to such irregularities (see Fig. 10). In Fig. 7, which is replotted from Fig. 18 of ref. 6, the buckling stresses of some 150 curved plates are given; for certain groups of these plates, the minimum average stresses after buckling are plotted on Fig. 8, obtained from Figs. 22 *a* and *b* of the same report.

The reduction in scatter on the second diagram is obvious. For comparison, the minimum post-buckling values for ideal plates from Fig. 6 have also been plotted on Fig. 8; strictly speaking this comparison is vitiated, because both theoretical and experimental results jump the true trough by different amounts for quite different reasons. However, the theoretical curves are flat

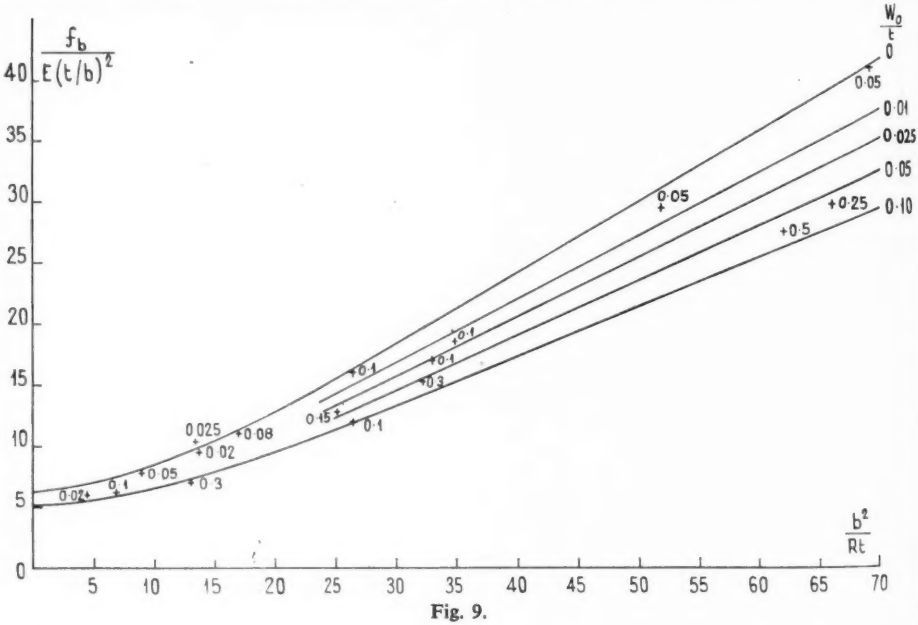

Fig. 9.

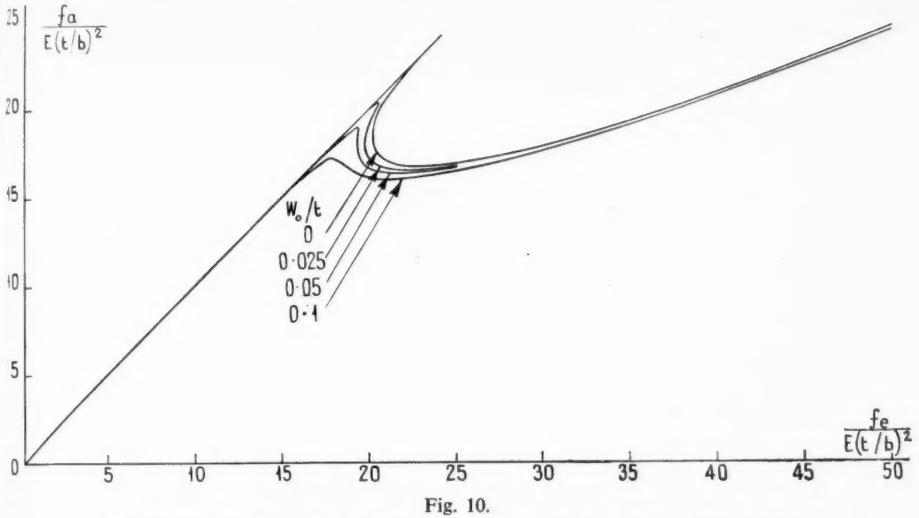

Fig. 10.

Theoretical load-deflection curves for curved plates with initial irregularities.

around their minimum values and the good general agreement indicates that the parameters in the theoretical formula have been suitably chosen to represent reasonably well the behaviour of curved plates in the early post-buckling range.

Buckling stress and initial irregularities.

For 18 plates both the buckling stresses and the initial contour shapes are given in ref. 6. These data afford an opportunity to correlate the amplitude of initial irregularities, as expressed by the ratio W_o/t in equations (34) and (35), with the actual deviations from the ideal shape of the plates tested. It would be inappropriate to take the maximum deviation from the cylindrical shape anywhere on the plate and compare this with W_o; for W_o represents a periodic irregularity, corresponding in position and direction to the buckles which later develop in the individual plate. Rather should we attempt to measure the average deviation over a length equal to the wavelength of the buckles. Yet this wavelength is not precisely defined and varies from plate to plate, so that the best we can do is to measure the deviation over some arbitrarily chosen length. Therefore, we designate by δ the maximum inward deviation of the plate surface from a straight edge of length b, placed anywhere on the plate along any generator; and we expect to be able to correlate δ to W_o by a simple invariable constant of proportionality.

In Fig. 9 the values of buckling stress coefficients for 18 plates have been plotted on a diagram showing curves of buckling stress coefficients for constant values of W_o/t; values of δ/t for the individual plates are also shown. Comparison of the values of δ/t with the corresponding W_o/t values indicates an average ratio of δ/W_o of the order of 3.

It may be of interest to note that the two points closest to the theoretical buckling value of ideal plates are those of plates which have a slight outward bulge extending along the entire centre part of the plates. The buckling stresses of plates with outward bulges on their initial shapes are uniformly higher than those of plates with equivalent inwards bulges, but of the 155 plates tested none exceeded substantially the theoretical buckling value.

Load carried by curved plates after buckling.

The buckling stress of a curved plate of given width and thickness increases steadily and—except for nearly flat plates—almost linearly with increasing curvature. The effect of increasing curvature on the load carried after buckling is less well established.

The theoretical curves of Fig. 6 intersect at certain strain values, so that at high strains the plates curved to the smaller radii

carry less load. From the experimental results no certain conclusions can be drawn at this stage; the general tendency of the slope after buckling to diminish with increasing curvature is overlaid by a number of secondary effects which are caused in part by change of buckled wave form and in part probably also by plastic deformation at the buckles. The most that can be said is that the difference in load carrying capacity at small values of b^2/Rt (<15) is likely to be negligible in comparison with the variations due to differences in lateral restraints and plate length. For large degrees of curvature, the plate will certainly carry less load than a flat plate of the same dimensions, but at what value of b^2/Rt the reduction will approach that of the full cylindrical shell is still uncertain.

References

1. Th. von Kármán and Hsue-Shen Tsien. The Buckling of Thin Cylindrical Shells under Axial Compression. Journal of the Aeronautical Sciences, June 1941.
2. D. M. A. Leggett and R. P. N. Jones. The Behaviour of a Cylindrical Shell under Axial Compression when the Buckling Load has been Exceeded. R.A.E., S.M.E. Report No. 3204 (ARC number 6135), 1942.
3. W. T. Koiter. Over de stabiliteit van het elastisch evenwicht (Dissertation), Amsterdam, 1945.
4. K. Marguerre. On the Strength of Shells of Small Curvature. Proceedings 5th International Congress of Applied Mechanics.
5. H. L. Cox. The Buckling of a Flat Rectangular Plate under Axial Compression and its Behaviour after Buckling. Aero. Res. Council, Report and Memorandum No. 2041, 1945.
6. K. B. Jackson and A. H. Hall. Curved Plates in Compression. National Research Council of Canada, Report No. MM-180, 1945.
7. D. M. A. Leggett. The Buckling of a Long Curved Panel under Axial Compression. Aeronautical Research Council Rep. & Mem. No. 1899, 1942.
8. G. Welter. Curved Aluminium Alloy Sheets in Compression for Monocoque Constructions. Journal of the Aeronautical Sciences, July 1945.

Bibliography

This bibliography is not exhaustive, but is intended to give a review of papers relevant to the subject.

9. Southwell. General Theory of Elastic Stability. Phil. Trans. A. Vol. 213 (1913).
10. E. Chwalla. Collapse of Tubes under End Thrust. Z.A.M.M. 10, p. 72 (1930).
11. S. C. Redshaw. Elastic stability of a thin curved panel. A.R.C. R. & M. 1565. May, 1933.
12. E. E. Lundquist. Strength tests of thin-walled duralumin cylinders in compression. N.A.C.A. Report No. 473. 1933.
13. L. H. Donnell. A new theory for the buckling of thin cylinders under axial compression and bending. A.S.M.E. Trans. Vol. 56, No. 11. November, 1934.
14. Heck and Ebner. Formeln und Berechungsverfahren fuer die Festigkeit von Platten und Schalenkonstruktionen. Luftfahrtforschung, Vol. XI, p. 221 (1935).
15. Gerard and Dickens. Stressed-skin structures. Compression tests of panels with tubular stiffeners. A.R.C. R. & M. 1830, Dec., 1936.
16. Ballerstedt and Wagner. Versuche über die Festigkeit dünner unversteifter Zylinder unter Schub-und Längskräften. Luftfahrtforschung Vol. 13, No. 9, p. 309. September, 1936.
17. Ebner. Theorie und Versuche zur Festigkeit von Schalenruempfen. Luftfahrtforschung Vol. XIV, p. 93 (1937).
18. Redshaw. Elastic stability of a curved plate under axial thrusts. J. R.Ae.S., Vol. 42, 1938.
19. W. A. Wenzek. The effective width of curved sheet after buckling. N.A.C.A. T.M. 880.
20. Kanemitsu and Nojima. Axial compression test of thin circular cylinders. Calif. Inst. Tech. Thesis. 1939.
21. Kármán, Dunn and Tsien. Influence of curvature on the buckling characteristics of structures. Jnl. Aero. Sci, p.276. 1940.
22. Cox and Clenshaw. Compression tests on curved plates of thin sheet Duralumin. A.R.C. R. & M. 1894. November, 1941.
23. E. E. Lundquist. Preliminary data on buckling strength of curved sheet panels in compression. N.A.C.A. A.R.R. 24. Nov., 1941.
24. J. R. Fischel. The compressive strength of thin aluminium-alloy sheet in the plastic region. Jnl. Aero. Sci., p. 373. Aug., 1941.
25. Roark. Stresses and deflections in thin shells and curved plates due to concentrated and variously distributed loading. N.A.C.A. T.N. 806. 1940.
26. Levy, McPherson and Ramberg. Effect of rivet and spot-weld spacing on the strength of axially loaded sheet-stringer panels of 24 S-T aluminium alloy. N.A.C.A. T.N. 856. Aug., 1942.
27. E. Stowell. Critical compressive stress for curved sheet supported along all edges and elastically restrained against rotation along the unloaded edges. N.A.C.A. R.B. 3107. September, 1943.
28. Lundquist and Schuette. Critical stresses for plates. N.A.C.A. A.R.R. 3L27. October 1943.
29. S. Levy. Large deflection theory of curved sheet. N.A.C.A. T.N. 895. May 1943.
30. Crate and Levin. Data on buckling strength of curved sheet in compression. N.A.C.A. A.R.R. 3L04. October 1943.
31. M. Holt. Tests of aluminium-alloy stiffened-sheet specimens cut from an airplane wing. N.A.C.A. T.N. 883. January, 1943.
32. Some investigations of the general instability of stiffened metal cylinders. Part 4. N.A.C.A. T.N. 908. August, 1943.
33. McPherson, Fienup and Zibritosky. Effect of developed width on strength of axially loaded curved sheet stringer panels. N.A.C.A. A.R.R. 4H08. November, 1944.

34. RAMBERG, LEVY and FIENUP. Effect of curvature on strength of axially loaded sheet-stringer panels. N.A.C.A. T.N. 944. August, 1944.

35. H. L. COX. Note on the buckling of curved plates under axial compression. A.R.C. Report No. 8406. February, 1945.

36. DEI POLI SANDRO. Il comportamento elastico delle pareti di forma cilindrica non perfetta, soggette a compressione. Politecnico di Milano. October, 1945.

37. G. WELTER. Influence of different factors on buckling loads of curved thin aluminium-alloy sheets for monocoque constructions. J. Aero. Sci., p. 204. April, 1946.

38. G. WELTER. The effect of radius of curvature and preliminary artificial eccentricities on buckling loads of curved thin aluminium-alloy sheets for monocoque constructions. J. Aero. Sci., p. 593. November, 1946.

39. STOWELL. Critical compression stress for curved sheet supported along all edges. N.A.C.A. R.B. 3107. 1946.

40. BATDORF, SCHILDCROUT and STEIN. Critical stress of thin-walled cylinders in axial compression. N.A.C.A. T.N. 1343. June, 1947.

41. BATDORF. A simplified method of elastic-stability analysis for thin cylindrical shells. 1: Donnell's Equation and 2: Modified equilibrium Equation. N.A.C.A. T.N. 1341 and 1342. June, 1947.

42. DEI POLI SANDRO. Sul calcolo delle pareti cilindriche compresse secondo le generatrici. Politecnico di Milano. June, 1946.

43. DEI POLI SANDRO. Ricerche sperimentali sulle pareti cilindriche compresse secondo le generatrici. Politecnico di Milano. February, 1947.

44. DEI POLI SANDRO. Sulla stabilita elastica della striscia cilindrica compressa secondo le generatrici. Accademia delle Scienze di Torino. Vol. 81. 1946-47.

CORRESPONDENCE

AIRCRAFT ACCIDENTS

To my mind, the answer to the query "Can chances of survival be increased?" (Aircraft Accidents, R. E. Hardingham, July 1948 Journal) is definitely, "Yes," and the toll of human lives due to aircraft accidents has once again produced a paper that should encourage serious thought and remedial action.

The difficult problems facing a designer wishing to design an aircraft that will not kill, or burn to death, its occupants in the event of an unpredictable accident, are appreciated. Such an aircraft would increase manufacturing and operating costs so far as payload was concerned and might result in the loss of a contract that might have been won, had such safety designs been omitted.

Because of these difficulties, the trend appears to be to dismiss the issue by saying "I don't know how many of the occupants of this aircraft would survive in the event of a crash, but let's not think of such things. It might never happen." True, it might never happen, *but*, it has only to happen once, then it is too late to discuss it.

Among the many crashes which I have witnessed, in nearly 27 years service in the R.A.F., was one in which a twin-engined aircraft stalled at 500 ft., when executing a turn at the end of a down-wind leg, preparatory to landing. This crash occurred within sight of the airfield and the injuries sustained by the majority of the nine occupants were such that they would not have lost their lives from these alone, but they were so quickly enveloped in flames of such great intensity that rescue was not possible.

In my opinion the precautions taken against loss of life caused by fire occurring after crashing are totally inadequate. Comparisons are odorous, but facts must be faced. Compare the extent to which precautions and safeguards are taken, and rigidly enforced, in spheres of human activity other than flying: the precautions taken in large buildings for instance, the provision of fire doors, escapes, clearly marked exits, fire fighting equipment, display notices clearly stating action to be taken, and notice of danger, by alarms, to the occupants; the boat and fire drill aboard ships in which the *passengers* take part; and the fire drill and practices made in schools and camps. Those responsible do not dodge the issue by saying: "Why worry, it might never happen." They know only too well that it *can* and *does* happen. So, for that matter, do designers and operators of aircraft know. But what is the authority whose duty it should be to force designers and operators to make provision against loss of life? Weight factors and payload should not be the means of preventing such provisions from being incorporated in every aircraft, military or civil, and certainly not in passenger-carrying air liners.

Costly and elaborate precautions and equipment are incorporated in aircraft carriers, the effectiveness and life-saving properties of which have proved that the money expended has been well worth while. As an example of this I quote from personal experience, having been aboard a certain aircraft carrier in the Bay of Biscay when a fire occurred in an aircraft hangar. A squadron and a half of aircraft, fully filled with petrol, were totally destroyed without injury to or loss of life of one of the 1,000 or more people aboard, and with comparatively little structural damage to the carrier itself. Prompt action by one of the R.A.F. maintenance personnel in setting the fire fighting equipment in operation confined the fire to one section of the ship and extinguished it. This fire could have had serious consequences had the safeguards not been provided or had the personnel aboard been unaware of their existence and method of operation.

The point I wish to make is, it *can* and *does* happen, but well thought out design can greatly reduce loss of life when it does happen.

It is agreed that such extensive arrangements as employed on an aircraft carrier would be difficult to employ on aircraft but, surely it should be the adequacy of the protection afforded that should be aimed at and this will differ with the different types of aircraft and the purposes for which they are used. Cannot the pitiable efforts now made for the safeguarding of life in crash fires be improved?

These safeguards at the present time consist of the following:—

(*a*) Fireproof bulkheads behind engines—of use only in the case of an engine fire in the air and not always successful and not practicable with a jet engine.

(*b*) The system of impinging extinguishing mixture on places of possible fire outbreaks in the air—in their present form of no use in crash fires caused by the bursting of fuel tanks.

(*c*) Hand operated extinguishers—invaluable perhaps in the event of small outbreaks of fire, while the aircraft is on an even keel and the passengers and crew are uninjured and composed; useless in a crash. How many of the passengers know where these are located and how many would be capable of reaching and operating them after the aircraft wing had hit the side of a house? The same may be said of fire axes and first aid kits.

How many passengers are instructed before flight as to the location of fire fighting equipment and emergency doors? How many know how to operate these? What instruction is given to passengers on the action to be taken after a crash or ditching? Do aged and infirm passengers and children know where the dinghies are, how to get into them and how to behave when they are embarked?

The R.A.F. went to great trouble to instruct air crews in dinghy drill. Perhaps the giving of necessary instructions to passengers, some of them seeing the inside of an aircraft for the first time, is considered to be one of the things that is "not done," and likely to alarm passengers unduly when, "It might never happen."

What is being done to stamp out designs in aircraft which, although structurally sound under normal conditions, are a real danger and the cause of fire occurring in the event of a crash? I have in mind the method of installation of the petrol tanks of a well-known twin-engined bomber. The tanks are fitted into the open end of the wing roots and have spigots some 4 in. long riveted to their sides to marry up with recesses in the centre section. When this type of aircraft crashes, as many of them did, the spigots are torn out of the side of the tank and the petrol gushes out on to the engine exhausts. I do not mean to imply that this happened in every case, but to my mind this type of design should never have been allowed to pass the drawing board stage.

The chances of survival in the event of a crash where fire occurs are very remote indeed.

Aircraft and airfield owners provide fire and crash vehicles which are located *on airfields*. Admittedly quite a number of crashes occur on, over and near airfields, but what of those that occur some distance away, in surroundings where vehicles cannot approach the aircraft, *e.g.*, on a mountain side or in the water? How many civil fire engines have equipment to fight aircraft fires, or asbestos suits for rescue work?

Crashes have occurred where the resultant damage to the aircraft has been so great that it was not considered possible for any of the occupants "to get away with it," and yet the occupants have survived, while in other cases where there has been comparatively little structural damage, fire has occurred with fatal results to all on board.

The means of combating or preventing fires must be on the aircraft itself and not dependent on outside sources.

Much can be done, I think, but the lead must come from those who can exert the most pressure on the people responsible for the design and operation of aircraft and it should be international.

Would it shake airline operators if insurance companies refused to accept liabilities for loss of life, or aircraft, caused by fire after a crash or in the air?

Would air registration boards scrap their Cs. of A. and institute a new certificate called "Certificate of Air and Crashworthiness"—a C. of A. & C.? At least, for passenger-carrying civil air liners.

What can be done in the way of stimulating high pressure efforts by all concerned with aviation and others interested, to devise means of eliminating fire risks and reducing the amount of structural damage resulting from crashes? The National Press have been most generous in setting up competitions for air races, endurance tests, etc., which could, and have, resulted in the death of some of the participants. Would the Press consider offering a prize for a design that would reduce loss of life to a minimum in the event of an aircraft crashing, catching fire or ditching? Surely this would be a more deserving cause. Why not a Memorial Prize for such an effort, to be presented annually, with the added incentive that full patent rights would be given should any of the methods be adopted and become a requirement of a C. of A. & C.?

Some suggestions that might save life are:—

1. The cabins of all passenger-carrying aircraft to be lined with fireproof material, *e.g.*, asbestos sheeting, of sufficient thickness to withstand the threat of fire outside the cabin, with provisions made for positive blanketing off of certain portions of the cabin, say, from the rear span—aft. This would protect injured and uninjured until a safe exit was made or rescue effected.
2. The interiors of hollow constructional members of the aircraft, such as main spars, fuselage members, centre section positions, etc., might be filled with an extinguishing medium, in such a manner that the medium would escape, should any member fracture in a crash.
3. Fit an extinguisher in every seat or seat back, of sufficient capacity to cover at least one person with the medium. The occupant of the seat would be able to help to extinguish a portion of the fire, even if unable to extricate himself from his seat.
4. A complete spraying system throughout the aircraft, with tanks below the cabin floor or incorporated in the sides or roof of the cabin, acting as reservoirs. The operation of this system should be automatic and could be made to function if parts of the system, fitted in selected positions on the aircraft, were so constructed that damage to them by such force as is to be expected from violent contact with the ground, or obstructions in the flight path, would fracture them and set the system working.
5. In the event of ditching or forced landing in extremely poor visibility it is essential that the forward speed of the aircraft and contact with the ground, hillsides, or obstacles such as buildings, and contact with the water, should be such that the minimum amount of damage to the aircraft takes place. This is also true in conditions of good visibility where the ground is unsuitable for a safe landing.

   In all instances where speeds below stalling and negligible forward speeds are necessary to avoid damage to the aircraft and passengers, it is contended that parachutes could be employed easily and safely. Very heavy loads have been lowered from the air and I see no reason why aircraft, even large passenger aircraft, could not be lowered in the same manner.

   The parachutes could be released by the pilot and the attachments to the aircraft made after the manner of the fixing of lifting tackle to seaplanes for hoisting them aboard carriers. Greater use could be made of flotation bags for land aircraft which fly over large areas of sea.

   Balloons could be fitted that would automatically inflate and serve the dual purpose of keeping landplanes afloat on water, at any rate until the passengers could board the dinghies, and acting as a guide to rescue craft.
6. As Mr. Hardingham states, passengers tend to escape from crashed aircraft by the door through which they entered. Why should doors always be on the side of aircraft? Why not enter through the roof of the cabins?

Passengers attempt to escape through the entrance door chiefly because they are not aware of the existence of the emergency doors and escape hatches. All doors, hatches and exits should be fully opened when passengers are boarding the aircraft so that they may see them. Emergency doors should be as numerous as possible and be made to fall outwards by some spring mechanism when the emergency levers are operated. An operating lever should be provided near each site so that any passenger could operate it. The floors of the gangways should be "shuttered" so that they form a ladder in the event of an aircraft settling with its tail in the air.

J. Carroll (Wing Commander), A.F.R.Ae.S.

I was most interested in Mr. Hardingham's concise and timely paper, and think the following points emerge in particular and may contribute or not to accidents as the case may be:—

(i) In some cases we are trying to run before we can walk—I am thinking in particular of the very large aircraft which are being built in different parts of the world and for which there may not be sufficient—or adequate—aerodromes.

(ii) In the quest for reducing complications I feel that fixed undercarriages should be reverted to—it may look ugly and reduce aerodynamic efficiency, so dear to present-day designers, but we have a good example in the Bristol Wayfarer (well tried out) and, I believe, in the projected G.A.C. four-engined transport. The Avro York which was of low build could have been so fitted.

I feel sure that simplicity is the answer to fewer crashes.

(iii) I have often wondered why so many accidents have been caused by flying into rising ground, not necessarily much over 1,000 ft. above sea level. Surely on accepted routes and defined areas it is never safe to fly at less than 2,000 ft., for instance, on the London-Paris run (or reverse), where the North Downs have claimed so many victims? I take it the modern altimeter is correct to within a few feet?

(iv) Exits (both ordinary and emergency) have always puzzled me as in many cases they appear to be inadequate; emergency ones often appear to be in awkward places, to be of small size, and their operation not obvious to the ordinary person.

(v) I feel most definitely that the main answer to the reduction of accidents lies in the flying-boat which, for high capacity passenger-carrying, can be used to most countries of the world as is the ocean liner. If in time the flying-boat can be made amphibious so much the better, and if stub wings were fitted I do not see why they could not be used for the dual purpose of assisting stability in rough water and housing an emergency landing wheel gear.

H. C. Newton, A.F.R.Ae.S.

When considering Mr. Hardingham's paper on "Aircraft Accidents" I think we should take into account the two other logical arguments published in the July 1948 Journal, "Size of Transport" by A. Gouge and "Visual Aids for Low Visibility Conditions" by E. S. Calvert.

By formula and graph Mr. Gouge shows that the more the all-up weight of the aircraft is composed of passenger weight, the better will it be able to compete economically with ground transport over distances in excess of 100 miles. He mentions that the majority of fatal accidents occur during landing and take-off. Mr. Hardingham says that next to this the most frequent type of accident is that caused by flying into the ground in poor visibility.

Mr. Calvert admits that visual aids (and radio and radar aids) can only make things easier for the human senses to interpret: if the retina, the brain, or limb action of the human being in control of the aeroplane fail, ground aids cannot ensure that no disaster will result.

Mr. Hardingham ends his admirable paper with a plea for more research into the avoidance of crash, injury, and death; and asks that design organisations should be supplied with the fullest information on crashes to enable them to go far towards mitigating the present horrible results.

We are therefore faced with the facts:—

Aircraft will become larger, speedier and carry more passengers.

Successful landings must depend, finally, on the senses of one human being.

Aircraft must be designed so that there is every chance of survival if there is error of judgment on the part of the human being in control.

Injury and death in transport accidents result, almost always, from the fact that kinetic energy cannot tolerate unnatural dissipation. In aircraft accidents the dissipation is rapid, very often of the order of the schoolboy's problem of "irresistible force meeting immovable object" and the result is catastrophic. I think, therefore, it is reasonable to say that Mr. Hardingham's suggestions should be considered only as antidotes to the present design of the flying machine; the only solution for complete safety lies with the aircraft which can maintain itself in flight with negligible forward speed; or, at least, can dissipate most of its kinetic energy before meeting the "immovable object."

Nature has solved the problem by wind brake, variable wing loading and almost instantaneous control of power by the subject. Wind braking and control of power we have mastered; if we could solve the problem of variable wing loading in flight I suggest we would complete the trinity and rapidly develop the safe aircraft.

We are spending vast sums on aeronautics. Huge aircraft, such as the Brabazon and SR.45 will be flying within the next few years and supersonic flight is on the way. Surely it is reasonable to suggest that much of this money would be better spent on solving the problem of the uncrashable aircraft, rather than in producing bigger and faster ones which can only maintain flight by very high forward speed.

The problem is not insoluble, the results, in the view of many, would be more important than the jet.

R. A. B. Stone (Group Captain), A.F.R.Ae.S.

Two points which should be mentioned in connection with aircraft accidents are:

(1) *Bag Fuel Tanks.*—These tanks are considered much safer because of their pliability in the event of a crash. Invariably welds or rivets in tanks suffer through periods of vibration and the fuel then seeps over surfaces and is readily ignitable in the event of a crash.

(2) *Oil Leaks at Joints of Power Plant.*—A strict observance of the rule not to allow any oil leaks whatsoever on the engines or auxiliaries is necessary. Observations made on numbers of these after a flight reveal numerous small or sometimes heavier coatings of lubricating oil on the outer casings which, mixed with petrol vapour (probably from the carburettor or supercharger casing in the crash), creates a slower burning mixture which would readily ignite the fuel from the pipes broken when the engine is torn away, probably a few seconds or minutes earlier than when the fuel is spilt.

In connection with broken fuel pipes, could not a non-return valve be placed in the fuel line in a rigid plane and thereby assist the automatic crash switch by cutting off the fuel, instead of the pilot having to operate cocks in a moment of anxiety?

The above points were observed during my service in A.I.D., M.A.P. during the late war.

H. C. Bevis, A.R.Ae.S.

The causes of landing and take-off crashes may be generally summarised as follows:—

On take-off—

(1) Engine failures.

(2) Structural (including tyre) failures.

(3) Unairworthiness because of incorrect rigging, or incorrect loading, causing accidents shortly after the aircraft has left the ground.

On landing—

(1) Under-shooting caused by engine failure, poor visibility or misjudgment.

(2) Over-shooting caused by brake failure, poor visibility or misjudgment.

(3) Structural (including tyre) failure.

Study of these causes shows that the designer can help matters considerably by improving reliability of engine and structure during the landing and take-off operations. The most straightforward method of accomplishing this is to reduce landing and take-off speeds and distances, thus reducing the time involved in the operations and reducing the impact speed should an accident occur.

In general terms, take-off speed and distance are mainly affected by the term (W/S) (W/Pto) and landing speed by (W/S) where

W = all-up weight of aircraft.

S = effective wing area.

Pto = power available for take-off.

In order to reduce take-off speeds and distances it is thus necessary to reduce the wing loading, the power loading, or both, and to reduce landing speeds and distances the wing loading should be reduced.

With current trends in high speed, high altitude flight, both wing loading and power loading tend to increase, since an aircraft designed for a high cruising speed is most efficient with a high wing loading, and the resultant decrease in drag has the effect of also increasing the most economical power loading.

With regard to short range aircraft, where the take-off and landing weights are similar, the final solution appears to be a choice between adopting lower wing and power loading basically, or altering the wing loading by means of special flaps or extending wings, or increasing $C_{L\max}$ by means of slots, slats, boundary layer control and so forth. On analysis, it is probable that the simpler expedient of increasing (W/S) and (W/Pto) basically proves the more economical, as both methods involve similar increases in structure weight, with corresponding reduction of payload. Since the payload on a short haul is in any case comparatively high, the effect of increased structure weight is less significant and seems a small price to pay for increased safety.

For aircraft ranges where there is a marked difference in take-off and landing weights, because of consumption of fuel, the landing problem is automatically catered for by reduction of W, but the take-off case still remains, and by far the most economical way of assisting take-off is to reduce W, the effect being proportional to W^2. This can be done, without sacrifice in cruising efficiency, by taking-off with just sufficient fuel to climb and cruise for say, one hour, and then refuelling to the maximum permissible all-up weight in the air. Not only can take-offs be made safer in this manner, but for really long ranges the margin of weight saving can be such that additional payload can be carried at the same time.

As an example of the type of safety with economy that can be achieved in this manner, consider a 100 ton air liner flying from London to New York, requiring 30 tons of fuel for the journey. If the aircraft were to take-off with two tons of fuel for climb and one hour's cruising, the take-off weight would be reduced to 72 per cent. of the maximum and the take-off distance to approximately 52 per cent. of that for a fully loaded aircraft. If, however, a take-off run of approximately 70 per cent. were acceptable for safety purposes it would only be necessary to reduce take-off weight to 83.6 tons, that is to say, that an extra 11.6 tons of payload could be carried, fuel for the journey being added in two air refuelling stages, so that the maximum permissible all-up weight is not exceeded. In this way, not only is take-off made safer, and payload increased, but travellers between termini are not subjected to the hazards of landing and taking-off at intermediate refuelling stops.

P. S. Macgregor, B.Sc.(Eng.), A.F.R.Ae.S.

(The above letters, received in connection with the paper "Aircraft Accidents, Can Chances of Survival be Increased" (July 1948 Journal), together with a number

received personally by Mr. Hardingham, are all in general agreement with Mr. Hardingham's arguments.

Mr. Hardingham does not consider that specific and individual answers are needed, except for Wing Commander Carroll's suggestion for a "Certificate of Air and Crashworthiness." Mr. Hardingham states that both the I.C.A.O. Requirements and British Civil Airworthiness Requirements already contain certain "crash-worthiness" provisions. As the British Requirements constitute the basis on which the Air Registration Board makes its recommendations to the Minister of Civil Aviation for the issue of Civil Airworthiness Certificates, the certification which Wing Commander Carroll suggests is, in effect, already provided.

Letters from readers who disagree with any of the views expressed in Mr. Hardingham's paper, or the above letters, will be welcomed. The views of designers would be particularly interesting. There are different aspects of this important subject which should be given proper presentation.—ED.)

THE EVOLUTION OF THE DESIGN OF AN AEROPLANE

I would like to add a point or two to Professor Lickley's stimulating paper, "The Evolution of the Design of an Aeroplane," in the June 1948 Journal.

Professor Lickley rightly stressed the importance of mutual co-operation between members and sections of the design team; I would suggest that this team should include the test pilot, from Stage 3 (at the latest) onwards.

The time is past when test pilots, with a few brilliant exceptions, were employed solely to take the risks on behalf of the technicians. That the properly trained test pilot with a sound technical background can be of great assistance to the design and development teams is recognised by the Ministry of Supply, one of whose establishments (E.P.T.S.) provides a training unequalled anywhere in the world, and by many firms and services in this and other countries who seek to acquire pilots so trained.

The human factor plays a large part in the operation of any aircraft, as accident statistics show. The efficiency of the pilot is greatly affected by cockpit comfort, convenience, complexity of ancillary systems and controls, fatigue, and last, but by no means least, the physical sensations derived from the aircraft's handling characteristics. The first three of these matters can be considered early in the life of the design—the earlier the better. (Altering the mock-up is cheaper than altering the prototype.)

The development of pleasant handling characteristics as distinct from mathematically adequate control and stability is a process in which the opinion of the test pilot (who represents the customer) should weigh heavily.

I am sure that Professor Lickley will agree that full co-operation (not always readily forthcoming!) with the C.T.P. and his staff, beginning at an early stage in the design, can prevent much waste of time and money and materially assist in the production of a good aeroplane.

D. J. Masters, A.R.Ae.S.

Mr. Masters' comments on the inclusion of the test pilot in the design team are of interest. I agree with him that the test pilot should come in at Stage 3, but did not mention this specifically in my lecture as I felt it was normal practice. I do not understand his comment about co-operation not being readily forthcoming, but would agree with him that co-operation with the test pilot is always a great advantage to the design of the finished product.

R. L. Lickley, F.R.Ae.S.

PLANNED SERVICING OF AIRCRAFT

I was very interested to read the letter from Squadron Leader E. A. Harrop in the June Journal, partly for his references to "Planned Flying and Planned Servicing," which at last seems to be coming into its own, but more particularly for his remarks on hangars.

The development of the hangar is one of the least imaginative aspects of aircraft maintenance, for it has followed the line of building bigger and bigger sheds into which to push bigger and bigger aircraft; regardless of the lost space arising from the scale effect, and of the needs of the aircraft once it is inside. The latter is the key point, because efficient maintenance demands the static servicing dock by means of which labour and materials are brought to the point of application on the aircraft. If the structure of the dock can be extended to provide shelter for the men working on it, the superstructure of the hangar serves little purpose.

Timber servicing docks such as those used for the Skymaster by the U.S. Army Air Force Transport Command at Morrison Field, Florida, in 1946, provided ideal conditions for the " planned inspection " at negligible cost; and it seemed that they could be weather-proofed without great difficulty. American service opinion at the time appeared to be that for large aircraft the hangar was no longer practicable. In the civil field the " nose hangar," such as that used successfully by KLM for the Constellation last winter, is a realistic effort to provide shelter where it is needed, instead of enclosing space at random.

Squadron Leader Harrop's octagonal project is admirable for disposition, but appears to aim at complete cover in each bay, and I would suggest that it be modified to provide working essentials only.

S. D. McDonald, A.F.R.Ae.S. (Economic Research Officer, B.O.A.C.).

In general I agree with Mr. McDonald's comments regarding unimaginative hangar design by merely enclosing space at random. I think, however, that we must be careful to differentiate between a " nose servicing hangar " and a " dock servicing hangar."

Before considering the differentiation of hangars, it is essential to remember that the capital costs of hangarage can only be kept down by high utilisation of the hangars (of whatever type) by quick turn-round of servicing operations, *i.e.*, by " planned servicing." Quick turn-round reduces the number of aircraft on the floor and, consequently, the hangar accommodation required. The capital expenditure on the required hangars and equipment, and increased wages for shift working, etc., must then be measured against the increased utilisation of aircraft thereby obtained.

The " nose hangar " is probably the most economic hangarage for impermanent conditions, such as first line servicing in the field. Its cost is low and some shelter can be provided if required for the servicing personnel working on the aircraft. But so far as weather is concerned I can only consider it as an improvisation.

When considering the weather, especially in the U.K., Canada and the European Continent, I think that total enclosure of the aircraft in a " servicing bay " is necessary for second line servicing at permanent base stations. The productive output of servicing personnel is greatly affected by weather and to keep the working conditions normal requires totally enclosed and heated hangarage. Each aircraft bay can then be made into a " dock " in the true sense with all power, light, heat, gantries and scaffolding laid on. The octagonal layout of such aircraft bays or docks offers the greatest concentration of servicing facilities and those allied to them, such as workshops, stores and administrative offices.

From the military aspect there are other considerations, for example, servicing also includes inspection and repair of battle damage of the whole aircraft structure and therefore its total enclosure for work on it.

E. A. Harrop (Squadron Leader), O.B.E., A.F.R.Ae.S.

REVIEWS

Theory of Propellers by Theodore Theodorsen. Published by McGraw-Hill & Co., 1948. 21/- net.

This is an attractive book because it describes in detail the author's theory of propellers. The theory is based on the wake infinitely far behind the propeller and can be applied to problems not previously soluble by the momentum theory or its extensions. The propeller problem is treated in exact terms for the wake, and the wake parameters are considered the primary ones, *e.g.*, the thrust coefficient is referred to the diameter of the wake helix far behind the propeller.

The theory is developed for single and dual propellers and refers in considerable detail to the effect of interference. The application of the theory to propeller design is discussed in detail and excellent tables and diagrams are given.

The book is excellently produced and can be warmly recommended to anyone interested in propeller theory and design.

Wind Tunnel Testing. Alan Pope. John Wiley & Sons Inc., New York, and Chapman and Hall Ltd., London, 1947. 376 pp. Illustrated. Diagrams and photographs. $5.00 net (£1 10s. 0d. net).

It is a far cry from the tests inaugurated by the Royal Aeronautical Society in the first wind tunnel in the world, in 1870, to the wind tunnels of the present day. Considering the fundamental importance of wind tunnel testing it is remarkable that there have been so few books on the subject.

Professor Pope is the Associate Professor of Aerodynamics at the Daniel Guggenheim School of Aeronautics, Georgia School of Technology, and in the book under review he has collected together a great deal of scattered information which is of interest and use to aerodynamicists.

Chapter I gives a description of various types of wind tunnels and a reasonably complete list of wind tunnels of the world. Most of the tunnels listed are pre-, or early, war, and many listed, especially in the enemy countries, are now no longer in use. Security reasons have prevented the listing of some of the more interesting tunnels.

Chapter II covers wind tunnel design and the following chapter, calibration of the wind tunnel jet. The measurements of model forces, movements and pressures are dealt with in Chapter IV and Testing Procedure in Chapter V (a most useful chapter). Wind tunnel boundary corrections are discussed in Chapter VI and Extrapolation to full scale in Chapter VII. The last two chapters are concerned with Auxiliary Testing Equipment and Small Wind Tunnels.

This book is valuable for the many worked out examples appearing throughout the text and the problems set at the end of each chapter. It is excellently produced.

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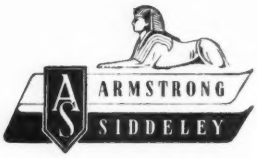

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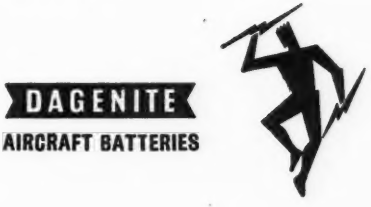

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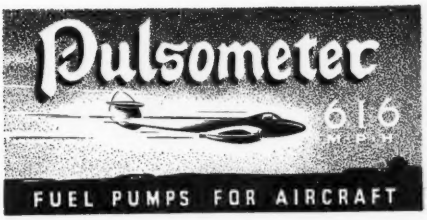

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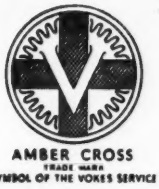

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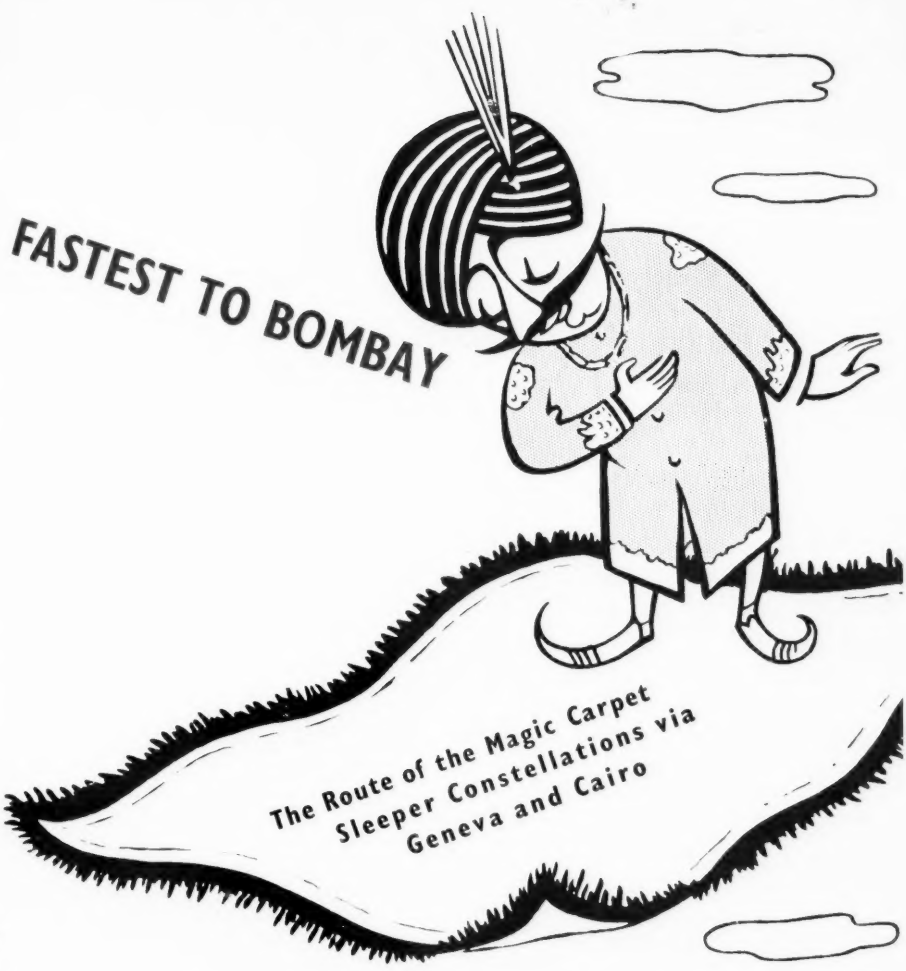

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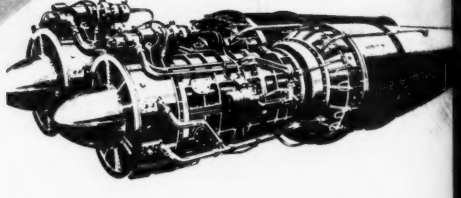

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